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EVALUATION OF SOLIDIFICATION/STABILIZATION AS A BEST DEMONSTRATED AVAILABLE TECHNOLOGY FOR CONTAMINATED SOILS

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16. ABSTRACT

This project involved the evaluation of solidification/stabilization technology as a BDAT for contaminated soil from Superfund Sites. Three binding agents were used on four different synthetically contaminated soils. Performance evaluation data included unconfined compressive strength (UCS) and the Toxicity Characteristic Leaching Procedure (TCLP) leaching test. Results indicated that solidification/stabilization techniques were effective in reducing the leachable metals of the contaminated soils.

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This project evaluated the performance of Solidification/Stabilization (S/S) as a means of treating soil from "Superfund" sites. Tests were conducted on four different types of artificially contaminated soil that are representative of the types of contaminated soils found at Superfund sites. The soils were solidified using three commonly used S/S agents or binders. The resultant products were tested to determine whether the S/S binders reduced the water and air releases of the disposed soils.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

ABSTRACT

This project evaluated the performance of solidification/stabilization (S/S) as a means of treating soil from "Superfund" sites. Tests were conducted on four different types of artificially contaminated soil (called "Synthetic Analytical Reference Matrix" or "SARM") which are representative of the types of contaminated soils found at Superfund sites. The soils were solidified using the following three commonly used agents or binders:

1. Portland cement
2. Lime kiln dust
3. A mixture of lime and flyash

At 7, 14, 21, and 28 days after soil and binders were mixed, samples of the solidified/stabilized material were subjected to Unconfined Compressive Strength (UCS) testing. Samples of those mixes that had a UCS minimally greater than 50 psi (pounds per square inch) or which showed the highest UCS below 50 psi after 14 and 28 days were subjected to Toxicity Characteristic Leaching Procedure (TCLP) and Total Waste Analysis (TWA). The 50-psi level was chosen as a performance screening criterion based on guidance from the Office of Solid Waste and Emergency Response (OSWER Directive No. 9437.00-2A). The principal goal of this program was development of screening data in support of the BDAT regulations for contaminated soils. The schedule and experimental protocol were, therefore, geared to satisfying these regulatory demands.

As an ancillary goal, the results were analyzed to determine if any correlations could be obtained between the degree of toxicant immobilization, as determined by the TCLP, and the following other parameters:

1. UCS results
2. Curing time
3. Contaminant level
4. Binder type
5. Water concentration

The impact of these parameters on the leachability of the contaminants is complex. It was recognized at the start of the testing that this abbreviated set of experiments was not likely to adequately address all of these interactions. Furthermore, there is no set protocol for evaluating Solidification/Stabilization, although the leaching tests conducted here were consistent with the hazardous waste disposal regulations. Finally, only three types of generic binders were used. It is possible that other binders such as some proprietary ones which are designed for a given application would have yielded different results.

The following results were observed:

1. The water-to-total-solids ratio appears to be a better measure of the amount of water needed to solidify a given mix than the water-to-binder ratio that is commonly used. This was clearly the case for the SARMs with these binders. This hypothesis needs to be confirmed on other systems.

2. In general, solidifying/stabilizing the SARM resulted in significant reductions in the amount of metal salt contaminants released, as measured by the TCLP.

3. Solidification/stabilization did not appear to result in a similar reduction in the amount of organics released in the leachate as measured by the TCLP. Because of the large losses of organics during the mixing process, the effect of S/S on the organic constituents in the leachate via the TCLP could not be determined. The volatile and semivolatile organic contaminants did appear to decrease during the S/S process; however, this decrease can probably be attributed to their release to the air during processing and curing.

4. No correlation between UCS and the results of the leaching tests was observed.

This work was performed under Contract No. 68-03-3241, Work Assignment No. 2-18 from the EPA.

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SECTION 1

INTRODUCTION

The Hazardous and Solid Waste Amendments of 1984 require the U.S. Environmental Protection Agency (EPA) to develop treatment standards or treatment methods (called "Best Demonstrated Available Technology" or "BDAT") for listed hazardous wastes before disposal. Treatment methods are to be developed which reduce the toxicity or the likelihood of the migration of the hazardous constituents in the waste. The Superfund Amendment and Reauthorization Act (SARA or Superfund) requires that remedial actions meet all applicable, relevant, and appropriate public health and environmentalstandards. Therefore, the Superfund program may need to be consistent with the BDAT approach when contaminated SARMs and debris from Superfund sites are disposed.

EPA's Office of Research and Development (ORD) assisted the Office of Environmental and Emergency Response (OEER) in evaluating the five technologies listed below for background data for developing BDAT standards or methods for soil and debris.

1. Incineration
2. Low-temperature thermal desorption
3. KPEG reagent for dechlorination
4. Aqueous soil washing
5. Solidification/stabilization (S/S)

This project evaluated the performance of solidification/stabilization (S/S) as a means of treating soil from Superfund sites. Tests were conducted on four different types of artificially contaminated soil (called Synthetic Analytical Reference Matrix or SARM) which are representative of the types of contaminated soils found at Superfund sites. The SARMs were solidified/ stabilized (S/Sd) using three commonly used agents or binders. At 7, 14, 21, and 28 days after the SARMs and binders were mixed, samples of the S/Sd material were subjected to Unconfined Compressive Strength (UCS) testing.

Samples of those mixes that had a UCS minimally greater than 50 psi (pounds per square inch) or that showed the highest UCS below 50 psi after 14 and 28 days underwent Toxicity Characteristic Leaching Procedure (TCLP) and Total Waste Analysis (TWA). The 50-psi level was chosen as a performance

screening level consistent with guidance from the Office of Solid Waste and Emergency Response (OSWER Directive No. 9437.00-2A). The principal goal of this program was development of performance data in support of BDAT regulations for contaminated soils. The schedule and experimental protocol were, therefore, geared to satisfying these regulatory demands.

As an ancillary goal, the results were analyzed to determine if any correlations could be obtained between the degree of toxicant immobilization, as determined by the TCLP, and the following other parameters:

1. UCS results
2. Curing time
3. Contaminant level
4. Binder type
5. Water concentration

The impact of these parameters on the leachability of the contaminants is complex. It was recognized at the start of the testing that this abbreviated set of experiments was not likely to adequately address all of these interactions. Furthermore, there is no set protocol for evaluating S/S, although the leaching tests conducted here were consistent with hazardous waste disposal regulations. Finally, only three types of generic binders were used. It is possible that other binders such as some proprietary ones which are designed for a given application would have yielded different results.

The various portions of this program were performed by the following entities:

1. Mixing the SARM: PEI Associates, Inc., Cincinnati OH
2. Mixing the SARMs with the stabilizing agents, determining the acceptable water content, performing hardness and UCS tests, summarizing the results:

   Acurex Corporation, Research Triangle Park, NC
3. Total Waste Analyses (TWA): Hittman Ebasco, Arlington, VA
4. Toxicity Characteristic Leaching Procedure (TCLP):

   Lee Wan Associates, Atlanta, GA

For the purpose of this program, the optimum data would have been obtained if the UCS, TCLP, and TWA could have been performed at the same times or at least on the same day. To facilitate the necessary coordination, Acurex mixed the SARM and binder to the appropriate ratios and prepared samples from this mix which could be used for the UCS, TWA, and TCLP tests. The TWA and

TCLP samples were sent to the appropriate laboratories well before the date they were to be tested. On the scheduled date, the sample was subjected to the UCS testing. Each of the laboratories responsible for the analytical testing was immediately notified of the results and told which sample was to be tested. Unfortunately, conflicting laboratory schedules resulted in slippage in some of the dates when samples were subjected to analysis, although this slippage is not considered significant.

SECTION 2

CONCLUSIONS

The program described here had two major sets of goals. The first was to determine whether the Synthetic Analytical Reference Matrixes (SARMs) could successfully be solidified/stabilized and, if so, to assess how S/S affected a SARM's unconfined compressive strength (UCS) and the release of the contaminants as determined by the TCLP and by an approximate measurement of the volatile releases. The second, ancillary goal was to determine if any correlations could be obtained between the degree of toxicant immobilization, as determined by the TCLP and the following other parameters:

1. UCS
2. Curing time
3. Contaminant level
4. Binder type

The tests were conducted using three agents or binders:

1. Portland cement
2. Lime kiln dust
3. Equal weights of technical grade lime and flyash

The first conclusion that can be drawn from this program is based on an observation made during the initial screening tests. The original test matrix for this program was designed to determine the water-to-binder (W/B) ratio which would yield a product that hardened within the 28-day time frame of this program. Analysis of the early data showed that the water-to-total-solids (W/TS) ratio was a more consistent indicator of the amount of water needed to harden the mass than the W/B ratio.

This result may have been due to the high clay content of the SARMs or it may have a more general application. Further, the tests showed that, within the context of the experiment, a W/TS ratio of approximately 0.4 by weight produced a S/Sd product regardless of the binder used. This observation, if confirmed with other systems, could result in a significant reduction in the number of experiments required to test a series of waste/binder combinations.

Prior to discussing the conclusions regarding the strength of the S/Sd SARMs, it is important to note that the UCS, TWA, and TCLP are only a few of many tests which are intended to simulate the way a given material may behave in a landfill environment. No type of weathering or water resistance tests were performed on these samples. Contaminants such as those used here have been shown to decrease the solid's resistance to freeze-thaw cycles as well as to exposure to water.[4] Before these results are used for a given application, the situation should be assessed to ensure that these tests are appropriate and to determine whether other tests would also yield useful information.

In terms of overall strength as measured by the UCS, the portland cement produced the strongest product. Next stronger was the kiln dust, and then the lime/flyash. Typically, the portland cement resulted in a UCS exceeding 1,000 psi (the upper limit of measurement with the available equipment) for three of the four SARMs. Further, it achieved these levels at far lower binder-to-soil (B/S) ratios than the other two binders, resulting in a smaller volume of waste requiring ultimate disposal.

The strength of the product S/Sd with portland cement was significantly lower for SARM IV than for the other three SARMs. SARM IV was the most heavily contaminated material tested here: high organic/high metal. A high concentration of both types of contaminants (metals and organics) was required to weaken the SARM S/Sd with the portland cement. Neither SARM I (high organic/low metal) nor SARM III (low organic/high metal) showed the same dramatic decrease in strength.

The lime kiln dust and the lime/flyash mixtures used for these tests did not result in values of the UCS as high as those observed with portland cement, even for SARM IV. The samples S/Sd with these binders were generally very weak. The strength (UCS), however, continued to increase during the course of these tests. The trend in the data was very clear and confirmed the general impression that lime-based binders will continue to harden over a period of years. It may be that these binders, in the long run, can achieve the strength of portland cement for many wastes.

To assess the suitability of these two binders, the testing may have to span several months or longer, rather than the 28-day period of this test. The UCS values for these samples started very low, but as time progressed, they increased. The test suggests that the curing time for these binders should have been extended to determine how well the samples would cure over a 90- or 180-day period.

The program also included measurement of how the leachability and volatility of the contaminants in the SARM were affected by the S/S process. The leachability of the contaminants was tested by subjecting S/Sd samples of the SARM to a TCLP and a TWA.[5] The TWA is not intended to actually measure the leaching characteristics of a waste in a landfill environment as is the TCLP. It does, however, provide useful information to compare to the TCLP.

The results of the TCLP analyses for the metals were very encouraging. The data show that the metals leaching from the SARMs are reduced significantly by the S/S process. In fact, the reduction approached

100 percent for many of the compounds. The only metal salts whose leachability were not reduced by the S/S process were those which already exhibited a low leachability because of the natural stabilizing influence of the SARM itself.

The solid matrix of the uncontaminated SARM significantly reduced the concentrations of almost all the metals even without the binders. The TCLP results for the raw (unsolidified) contaminated SARMs were lower than the expected values for almost all the metals. Some of the metals could not be detected by the TCLP in the SARMs that had been heavily contaminated with metals (SARMS III and IV). Because the results were often very close to the detection limit, the data sometimes proved difficult to interpret. Nevertheless, the results clearly indicate a significant reduction in the TCLP of all of the metals when their concentration in the TCLP leachate was well above the detection limit. When it was close to or below the detection limit, a small increase was frequently noted. This may be a true phenomenon or an artifact of the test procedure. A detailed discussion of these results follows.

It should be noted that the pH of the liquid used to extract the samples for the TCLP was not measured after extraction was completed. The TCLP procedure requires that the liquid be buffered to a specified pH; however, because of the high alkalinity of the samples, the buffering capacity of the liquid may have been exceeded. In addition, while measurements were made of the metals content of the portland cement and lime kiln dust (as part of another project[2]) and none were found, no measurements were made of the metals content of the lime or of the flyash used. It is possible that the small amounts of some metals present in these components of the binder may have created a positive bias to the results.

All the binders reduced the TCLP leachability of the arsenic, cadmium, copper, nickel, and zinc. In all these cases, the S/Sd SARMs resulted in only trace amounts or less of these metals in the leachate. The TCLP results for lead were less consistent. All the samples that were S/Sd with portland cement showed very large reductions in the leachability of this ion. The kiln dust showed some reduction in the leachability of the lead, although the reduction was not as great as that for the portland cement.

The lime/flyash binder showed no apparent reduction in the TCLP leachability of the lead. In fact, the results actually showed an increase in the leachability after correcting for dilution. The increase is most likely due to the error introduced by the large amount of binder used for these samples and the resultant large dilution factor, rather than it being an actual increase. However, the results clearly showed no apparent reduction in the leachability of lead with this binder.

The S/S process had virtually no effect on the chromium ion in this program. In fact, as with the lead S/Sd by the lime/flyash mix, the TCLP concentration of chromium in the leachate appeared to increase after correcting the results of the TCLP on the S/Sd material for dilution. Chromium is one of the ions that was fixed by the SARM itself. It was not detected in the TCLP leachate of the raw SARMs I, II, and III and was only

detected at 0.06 ppm in the TCLP leachate of SARM IV prior to treatment. Its limit of TCLP detectability is 0.01 ppm. As a contrast, other metal ions were observed in concentrations ranging from about 6 ppm to nearly 400 ppm in the leachate from SARMs III and IV, which were spiked at the high metals level.

The reason for the negative results on the chromium for the three binders and (to a lesser extent) the lead with lime/flyash is uncertain. Table 2-1 lists the actual metal salts that were used to spike the SARMs and their solubilities in water. As can be seen, the solubility of the salts may not appear to be a factor. Similarly, both the lead and arsenic salts used are slightly soluble, yet they also behaved differently.

One possible reason for these results is that the SARMs themselves appear to bind the chromic oxide. As discussed above, the concentration of this ion in the TCLP leachate of the raw SARMs were very low. The S/S process may have caused an upset in the properties of the matrix which resulted in a slight increase in the release of the chromium salt. Conversely, the slight increase may be an artifact of the testing procedure used.

The metal compounds do not appear to be subject to chemical reaction with the binder. The metal oxides (represented here by zinc, arsenic, and chromium) may not be reacting with the calcium oxide and hydroxide in the binders. Conceivably, the calcium hydroxide in the lime-based binders could react with sulfates or nitrates, which are represented here by the salts of lead, cadmium, copper, and nickel; the results were not consistent enough to draw a conclusion. Further research into the chemical mechanisms involved in the S/S process is needed to resolve these questions.

TABLE 2-1. CHEMICAL IDENTIFICATION AND SOLUBILITY OF SARM METAL CONTAMINANTS

Chemical Type	Solubility in Water
Lead sulfate ($PbSO_4$)	Slightly soluble
Lead oxide (PbO)	Insoluble
Zinc oxide (ZnO)	Insoluble
Cadmium sulfate ($3CdSO_4 \cdot 8H_2O$)	Soluble
Arsenic trioxide (As_2O_3)	Slightly soluble
Copper sulfate ($CuSO_4 \cdot 5H_2O$)	Soluble
Chromium nitrate ($Cr[NO_3]_3 \cdot 9H_2O$)	Soluble
Nickel nitrate ($Ni[NO_3]_2$)	Soluble to very soluble

Another observation made from the TCLP data was that the results for each sample at 14 days were the same as those for the same sample at 28 days. This indicates that there is little reason to cure samples for the longer period. In fact, it would be desirable to compare the results for shorter time intervals. If this correlation could be confirmed, a significant reduction in the time required for such testing could be realized. This result is also of interest because it indicates that, at least for the

lime/flyash and the lime kiln dust, the UCS may not be a good indicator of how well metals are immobilized in the SARM. The UCS of the samples formed with these binders continued to increase, even though there was little change in the TCLP.

The TWA results for the metals appeared inconsistent. Before and after S/S, some of the metals showed large increases in concentrations and some showed decreases. These variations most likely are due to the variability associated with the results of the TWA "leveraging" of any error by the dilution correction. Overall, however, the results showed no clear-cut increase or decrease in the TWA for the metals from the raw contaminated SARM to the S/Sd material. The reason for this wide variability appears to be due to normal variability in the results of the TWA on different samples.

Wide variations in the TWA (after doping with the contaminants) were obtained by PEI Associates, Inc., on different samples of the same SARM. PEI took a number of samples of each SARM and subjected them to a TWA. Table 2-2 shows the results of the TWA samples that were obtained as part of this program. Table 2-3 shows the number of each that were so evaluated. The variabilities in the results were large. These results fell within the variability band identified by PEI. The reader is referred to References (1) and (6) for further details. Comparison of the two tables illustrates the levels of variability that were expected.

This high variability is probably due to sampling errors rather than analytical errors. It was determined that the size of the analytical error is small based on the TWA for the metals for each mix after 14 and 28 days. For example, SARM III, which was S/Sd with portland cement (PC) after 14 days (sample 7), showed 528 ppm arsenic. The same sample at 28 days showed 584 ppm. Generally, the metals analyses for each sample at 14 and 28 days agreed very well, which indicated that the analytical protocol gave reasonably consistent results. Although this conclusion is not pertinent to this discussion, the analyses also showed that the mixing procedures used in this program produced a homogeneous product.

The analysis of the volatile and semivolatile organic compounds in the headspace by a gas chromatograph equipped with a flame ionization detector (GC/FID) seemed to indicate that the emissions dropped only slightly from 14 to 28 days. This decrease is consistent with other research done by Acurex[2] which showed that in a stabilized sample, most volatile organic emissions occur during mixing; the rate continues at a steady rate after curing but drops as the organic content of the S/Sd material is reduced.

The S/Sd SARMs generally showed a lower TCLP value for the volatile organic contaminants than the original SARMs. The nature of this program did not permit quantitative evaluations of these releases, but analysis of the air in the headspace above the curing S/Sd samples clearly identified all the organic constituents present in the SARMs. On the basis of this information, it is reasonable to conclude that at least some of the organic constituents were released to the air, and as a result, no firm conclusions as to how well they were S/Sd can be drawn.

The TCLP for the semivolatile organics, in general, showed a significant decrease because of S/S processing. The results showed that the percent decrease in the TCLP leachate for the semivolatile organics was greatest for SARMs I and IV (those contaminated with high levels or organics) and least for SARMs II and III. SARMs II and III also showed a greater variability for the semivolatile reduction, but this is most likely due to analytical errors caused by the low concentration of the semivolatile compounds. However, large concentrations of the semivolatile organics were found in the headspace of the sample bags.

TABLE 2-2. RESULTS OF TWA FOR SARM SAMPLES RECEIVED FOR THIS PROGRAM

	Metals Concentration (mg/kg)			
Analyte	SARM 1 High organic, low metal	SARM 2 Low organic, low metal	SARM 3 Low organic, high metal	SARM 4 High organic, high metals
Volatiles				
Acetone	3,150	230	220	13,000
Chlorobenzene	330	9.2	8.9	270
1,2-dichloroethane	380	3.9	3.1	830
Ethylbenzene	3,350	74	100	2,500
Styrene	1,000	26	24	540
Tetrachloroethylene	710	16	13	540
Xylene	4,150	210	150	3,700
Semivolatiles				
Anthracene	940	275	265	775
Bis(2-ethylhexyl) phthalate	600	34	140	500
Pentachlorophenol	135	62	15	78
Inorganics				
Arsenic	18	18	904	810
Cadmium	17	23	1,280	1,430
Chromium	27	37	1,190	1,650
Copper	193	260	9,650	13,300
Lead	190	240	15,200	16,900
Nickel	27	32	1,140	1,380
Zinc	392	544	53,400	28,900

TABLE 2-3. RESULTS OF TWA FOR SARMS IMMEDIATELY AFTER MIXING[1]

(As determined by PEI
from main blend prior to shipping samples)

Analyte	Metals Concentration (mg/kg) SARM 1 High organic, low metal	SARM 2 Low organic, low metal	SARM 3 Low organic, high metal	SARM 4 High organic, high metals
Volatiles				
Acetone	4,500 (7)	360 (8)	360 (2)	8,030 (2)
Chlorobenzene	320 (7)	13 (6)	11 (2)	330 (2)
1,2-dichloroethane	380 (7)	7 (8)	5 (2)	490 (2)
Ethylbenzene	3,460 (7)	120 (8)	140 (2)	2,710 (2)
Styrene	730 (7)	48 (7)	32 (2)	630 (2)
Tetrachloroethylene	480 (6)	19 (8)	20 (2)	900 (2)
Xylene	5,720 (7)	210 (8)	320 (2)	5,580 (2)
Semivolatiles				
Anthracene	4,390 (7)	350 (7)	270 (3)	1,920 (3)
Bis(2-ethylhexyl) phthalate	1,830 (7)	140 (6)	270 (3)	1,920 (3)
Pentachlorophenol	270 (5)	40 (4)	30 (3)	80 (3)
Inorganics				
Arsenic	21 (8)	18 (7)	690 (4)	540 (4)
Cadmium	27 (6)	32 (6)	2,380 (2)	3,790 (2)
Chromium	30 (6)	32 (6)	1,260 (4)	1,400 (4)
Copper	260 (8)	280 (8)	9,550 (4)	11,250 (4)
Lead	270 (8)	320 (8)	15,100 (4)	15,680 (4)
Nickel	39 (8)	40 (8)	1,540 (4)	1,550 (4)
Zinc	570 (6)	680 (8)	34,450 (4)	28,660 (4)

Note: Values in parentheses indicate number of samples analyzed.

Based on this program, the decrease in the concentration of the volatile and semivolatile organics in the TCLP leachate cannot be attributed to the binding of the volatile compounds into the solid matrix by the S/S process. The decreases can also be explained by a simple release of the organic compounds during the mixing process and during the sample preparation (grinding and sieving) prior to extraction. Other work on this subject indicated that the handling and mixing associated with the S/S processes can result in the release of a large fraction of the volatile and semivolatile organics in a waste and that the release was only slightly dependent on the vapor pressure of the substance. It also showed that neither portland cement nor kiln dust/flyash produced an S/Sd product with a significant decrease in the release of organics to the air from the untreated waste.[2]

The fact that a decrease in the concentration of the volatiles in the TCLP leachate can be attributed to loss to the atmosphere is enhanced by the fact that the TWA analyses of the SARMs for volatile organics were much lower for the S/Sd than for the untreated materials. The S/Sd SARMs contained on the order of 80 to 90 percent fewer volatile organics than the original material. This is consistent with the hypothesis that the volatile organics were released to the air rather than trapped in the solid. Had the volatile organics truly been solidified, the TWA would have shown a constant value for these materials while the TCLP would have shown a decrease.

The TWA results for the semivolatile organics was unexpected. S/S appeared to result in an apparent increase in almost all the values, although this increase most likely is an artifact of the analytical method. The TWA results appear to have a very wide variation, which, although the reason for this is unclear, may be due to the physical nature of the semivolatile compounds. They are heavy solids that go into solution slowly. As a result, the amount of each constituent in the liquid for analysis after the extraction may be more of a function of how much of the material actually dissolves than of the total amount of that compound in the waste. Under normal conditions this error is not significant; however, in this case, the TWA values are corrected for dilution. This results in a "leveraging" of any error and a much higher degree of uncertainty for the TWA results.

In conclusion, it appears that S/S can reduce the leachability of many metals to near the normal detection limits. Even in this case when no effort was made to optimize the S/S process, most of the metal contaminants were effectively immobilized as determined by the TCLP. It is likely that with a proper choice of binder and avoiding interference compounds, it should be possible to S/S many inorganic contaminant.

Definitive conclusions concerning organic contaminants are another matter. There is strong evidence that the binders used in these tests did not appear to reduce their leachability at all. The act of mixing and handling the SARMs and binders did result in lower levels of organics in the S/Sd product; however, this reduction can be attributed to the loss of the volatile and semivolatile compounds to the air during mixing and curing. In fact, all the volatile and semivolatile organics were identified in the headspace air of the curing samples.

Attempts were made to correlate the following properties of the TCLP for the metal salts:

- o Leachability compared to time
- o Concentration of the metals in the leachate compared to UCS
- o Leachability of the metals in the leachate compared to the SARM composition.
- o Leachability of the metals compared to binder type

The comparison of leachability to time was tested by comparing the TCLP results for the samples at 14 and 28 days. The results for the organics were far too variable to permit this type of comparison. The TCLP for the metals, however, proved to be reasonably reproducible. These showed a high degree of reproducibility between the 14- and 28-day analyses. In fact, these data indicate that there is little reason not to rely on the 14-day tests. In almost all cases, the metals concentration in the TCLP extract for the 14- and 28-day tests was the same to well within normal errors in this test.

No correlation was found between UCS and leachability. On the other hand, the leachability was strongly related to the amount of metal in the SARM. The SARMs with a high metals concentration showed higher levels of the metals in the leachate than did those with a low concentration. The metals concentration in the leachate was not, however, affected by the organics in the SARMs. Both SARMs that had been contaminated with high levels of metals produced approximately the same quality leachate in the TCLP, even though one of them had been contaminated with low and the other with high levels of organics.

There is clearly a strong relationship between the leachability and the binder type. It is discussed above in greater detail. In these tests, the portland cement proved to be a superior binder by many criteria and appears to be the binder of choice of the three evaluated here.

SECTION 3

EXPERIMENTAL PROCEDURE

As briefly discussed in section 1, this program involved the evaluation of the effect of solidification/stabilization (S/S) on four types of Synthetic Analytical Reference Matrixes (SARM). The SARMs were prepared for EPA under a separate program and S/Sd using each of the following three different agents:

1. Portland cement, Type 1 (PC)

2. Lime kiln dust (KD)

3. Equal weights of technical grade lime and flyash (LF)

The portland cement was standard Type 1 manufactured by the W. R. Bonsal Company of Charlotte, North Carolina. It was identified as meeting ASTM specification C-150 and Federal Specification SS-C-1960-3A for Type 1 and 2. The lime kiln dust was obtained from the Mississippi Lime Company's plant in Ste. Genevieve, Missouri. The lime was hydrated agricultural lime manufactured by the Tennessee Lime Division of Tenn Luttrell Company, Luttrell, Tennessee. The flyash was a nonpozzolanic flyash obtained from a local power plant.

The testing on the SARMs consisted of the following steps:

1. Determine the amount of water present in each SARM and the amount that must be added to each binder/soil combination so that it will set into a monolithic block suitable for UCS testing.

2. Determine the minimum amount of binder needed to achieve 50-psi compressive strength as determined by ASTM Method C 109-86, Unconfined Compressive Strength (UCS) tests.

3. Determine the effect of S/S on the leaching characteristics of each binder/soil combination whose UCS, after 14 and 28 days of curing, minimally exceeded 50 psi or had the highest UCS if this value could not be achieved.

3.1 DESCRIPTION OF SARMs

The SARMs were prepared by PEI Associates, Inc. of Cincinnati, Ohio. The following four types of SARM were tested under this program:[6]

- o SARM I — Low metals, high organics concentration
- o SARM II — Low metals, low organics concentration
- o SARM III — High metals, low organics concentration
- o SARM IV — High metals, high organics concentration

Table 3-1 is a description of the uncontaminated SARM. It is a screened and washed mixture of sand, soil, gravel, and clay. Its composition also is given in table 3-1.

The clean SARM matrix was contaminated (under a different project[6]) to both a "high" and "low" level of the metal salts organic compounds. This resulted in the four SARMs which were used for this program. The target concentrations of the contaminants in each of the SARMs that were the goal (or target concentrations) of each constituent are shown in table 3-2. The clean SARM was doped with the specified materials by mixing it well in a small cement mixer and adding the target amounts of the contaminants to it. The mixture was then blended until it appeared homogeneous.

The material was tested for homogeneity by taking and analyzing multiple samples. The results of these analyses are summarized in table 2-3. As can be seen, some compounds appeared to have distributed themselves better than others throughout the SARM matrix, probably because the matrix absorbed some better than others. Two sealed 5-gal pails of samples from each of the four SARMs were shipped to Acurex. These were kept tightly sealed until the start of the program, at which time, the pails were opened, and samples of each of the four contaminated SARMs were taken.

Prior to being used in this program the contents of each pail were, thoroughly mixed manually. Then samples taken from different parts of the mixed material and put into a clean half-gallon bowl and again thoroughly mixed. Then samples were taken from different parts of the bowl and put into glass jars with Teflon-lined lids, and sealed. This procedures resulted in four jars of each SARM (a total of 16 jars) filled with essentially the same sample. These jars were sent to the laboratories for both TWA and TCLP analyses.

3.2 WATER REQUIREMENT TESTS

The first step in this program was a determination of the amount of water that needed to be added to each mixture of binder and SARM to obtain a mix that would set up into a monolithic mass. The water originally present in each SARM had to be included in the amount of water required for the S/S process, and this was determined for each of the SARMs as the first step in the program.

The water content of the SARM was measured by drying a known quantity to constant weight and attributing the weight loss to water removed by evaporation. To obtain this value, a known amount of SARM was placed in an

oven at 60°C overnight and reweighed the following morning. Sample weighing continued hourly until two consecutive readings did not differ by more than 1 percent. The apparent water content can be expressed as a percentage:

$$\%H_2O = 100\% \times (W_i - W_f)/W_i$$

where:

W_i = initial SARM weight
W_f = final SARM weight

Table 3-3 gives the water content of the four SARMs as determined at the start of this program and as determined during the preparation of the SARM.[4] As can be seen, the differences between the two values are small enough to be classified as sampling errors, indicating that no significant loss of water had occurred during handling.

TABLE 3-1. DESCRIPTION OF UNCONTAMINATED SARM[4]

Soil Component	Volume %	Weight %
Sand	20.0	31.4
Gravel (No. 9)	5.0	5.7
Silt	25.0	28.3
Top soil	20.0	19.8
Clay	30.0	14.8
- Montmorillonite	(7.5)	(5.4)
- Kaolinite	(22.5)	(9.4)
	100.0	100.0

Cation exchange capacity (Na), meq/100 g	133
Grain Size Distribution	
weight % sand	48
weight % gravel	7.5
weight % silt	33
weight % clay	12.5
TOC, mg/kg	3.2
pH	8.5
Moisture	Not analyzed; expected to be less than or equal to 5%

TABLE 3-2. TARGET CONTAMINANT CONCENTRATIONS FOR SARMS[6]

Analyte	Metals Concentration (mg/kg) SARM 1 High organic, low metal	SARM 2 Low organic, low metal	SARM 3 Low organic, high metal	SARM 4 High organic, high metals
Volatiles				
Acetone	6,800	680	680	6,800
Chlorobenzene	400	40	40	400
1,2-dichloroethane	600	60	60	600
Ethylbenzene	3,200	320	320	3,200
Styrene	1,000	100	100	1,000
Tetrachloroethylene	600	60	60	600
Xylene	8,200	820	820	8,200
Semivolatiles				
Anthracene	6,500	650	650	6,500
Bis(2-ethylhexyl) phthalate	2,500	250	250	2,500
Pentachlorophenol	1,000	100	100	1,000
Inorganics				
Arsenic	10	10	500	500
Cadmium	20	20	1,000	1,000
Chromium	30	30	1,500	1,500
Copper	190	190	9,500	9,500
Lead	280	280	14,000	14,000
Nickel	30	30	1,000	1,000
Zinc	450	450	22,500	22,500

It is recognized that this method resulted in nonaqueous volatile compounds appearing as water; however, these materials constituted no more than 1 percent of the weight of the contaminated SARMs, and the error was, therefore, not significant for this purpose. Once the water content of the SARMs was known, it was necessary to determine the approximate range for the water-to-binder (W/B) ratio which would result in an acceptable monolithic solid mix. Because of the short time frame that was available for these tests, the tests had to quickly identify an acceptable range, even if the result was less than optimum.

TABLE 3-3 WATER CONTENT OF SARM SOILS

SARM	Water content, % From these tests	From Reference 6
1	31.4	22.6
2	8.6	7.2
3	19.3	20.6
4	22.1	30.1

To perform the UCS tests, it was necessary for the S/Sd material to be a monolithic block, with no free liquid present except for a few drops on the surface. Preliminary tests were conducted, therefore, to see if the extremes of the above range of water content would result in such a product.

The amount of water required to form a satisfactory product was determined by preparing samples of each SARM at three levels of binder-to-soil (B/S) ratios for each of the three binders. Each of these resulting samples was then split into three portions, and each portion was mixed with a different amount of water.

The arbitrary values selected prior to the testing were B/S ratios of 0.20, 0.50, and 0.70 and W/B ratios of 0.20, 0.50, and 0.70. Using the portland cement mix, a set of samples in this range of values was prepared and allowed to cure overnight. None of these produced the monolithic, smooth mass which was defined as a suitable product.

The original protocol called for the samples to be mixed to slurry and molded in plastic cups. The samples were to be mixed in triplicate--three samples at each W/B and B/S value. They were to be cured at 70°C and 90 to 100 percent relative humidity for a period of 48 h, after which they were to be tested for penetration resistance using a U.S. Army Corps of Engineers Cone Penetrometer (CP) according to Army TM-5-530, Section XV.[3] The W/B ratio for each SARM which offered the most resistance to penetration was defined as the "optimal water percentage" and was to have been used in the B/S evaluations which followed.

Had the initial guess at the W/S and B/S range resulted in an acceptable product, this phase would have resulted in a total of 216 samples with the following variables:

2 B/S ratios (0.1 and 0.7)
x 4 Soil types
x 3 Binders
x 3 W/B ratios
x 3 --Triplicate samples
216 samples total

As it turned out, the above ratios did not result in acceptable products with any of the SARMs or binders. The first set of tests conducted with portland cement as a binder showed that no B/S ratio in the 0.1 to 0.7 range resulted in a product which would set up. Because no hardening resulted, the samples could not be tested. Based on this observation from the preliminary testing, the experimental protocol was modified in the following manner:

1. Small samples of each SARM/binder combination were made up over a very wide range of relative mixes.

2. Each of these combinations was then split into separate parts, and each part was mixed with a different amount of water. These parts were allowed to stand overnight, and those ratios of B/S/W (binder/SARM/water) that were set up were identified. The CP was used as an aid to this evaluation.

The middle of the range that resulted in a product which appeared to be hardening was then chosen as the midpoint of the next set of tests. In evaluating these data, it was noted that the water-to-soil or W/B ratios were not good indicators of the amount of water that should be used to form an acceptable product under these circumstances. It was noted, however, that the type of product produced could be correlated reasonably well to the water-to-solids (W/TS) ratio of the mix. This ratio is simply the mass of water used versus the sum of the solid component of the SARM and of the binder. In virtually all cases tested, a W/TS ratio of 0.4 to 0.5 resulted in an acceptable product.

A new test matrix was then set up to "home in" on the optimum amount of water that should be used for the subsequent testing, with the "optimum" as defined by the original test plan. This was done in the following manner:

1. The three B/S ratios were chosen at each end and the middle of this range. The middle value was the B/S ratio obtained from the preliminary set of tests described above.

2. For each B/S ratio, three or more samples of each SARM spanning the desired W/TS range were prepared.

3. The resulting mixes were tested with the CP after one day for signs of setting. The range of B/S and W/TS ratios that resulted in samples that showed signs of hardening were then used to establish a new test matrix. The high and low values for B/S ratios of the range replaced the 0.1 and 0.7 values in the initial test matrix, described above.

4. For each B/S ratio, mixes were prepared in duplicate at three (low, middle, and high) W/TS ratios spanning the range identified in step 3.

5. These duplicate samples were then used to establish a workable W/TS ratio following the procedure that was initially proposed for the program.

The procedure resulted in more than 216 samples. The results, however, showed that regardless of the SARM or the binder used, a W/TS ratio of approximately 0.4 resulted in some indications of hardening of the material.

3.3 PREPARATION OF BINDER-TO-SOIL MATRICES

Once an acceptable W/TS ratio had been established, tests were conducted to determine the minimum binder-to-soil, or more accurately binder-to-SARM, (B/S) ratio which would result in a sample with an unconfined compressive strength (UCS) greater than 50 psi. Actually, with some binders this UCS level could not be achieved in 30 days. This may have changed had the amount of binder been increased beyond the high levels used for these tests. In that case, the sample that achieved the highest UCS was used for subsequent testing.

The B/S ratio test was performed by mixing each SARM (4 SARMs) with each binder (3 binders) at three B/S ratios. Six samples of each mixture constituted one complete set. Five of these were molded into cubes for UCS testing. At 7, 14, 21, and 28 days, three cubes from each set were subjected to UCS testing, a destructive procedure which destroys the cube. The fifth and sixth sample were stored for future reference. Four samples of each mix were placed in glass jars with Teflon-lined lids and were sent to the laboratories for TCLP and TWA. The program resulted in a total of 648 samples, as shown below:

4	Soil types
x 3	Binders
x 3	B/S ratios
x 3	Triplicate samples
x 6	Samples at each condition
648	Total samples

Binder and SARM were mixed using the previously determined W/TS ratio. The amount of binder, SARM, and water was measured and recorded. Components of each mixture were added in the same order for each preparation.

The samples that were to be used for UCS testing were molded according to the specifications in ASTM C 109-86. The procedure calls for molding the material in specially fabricated stainless steel or brass molds, which result in cubes 2 in (5.08 cm) on each side. The procedure requires that the molds used meet strict dimensional and stiffness requirements. The resulting samples were allowed to harden for 1 to 4 days at 70 °F (±10 °F) and 90 to 100 percent humidity. They then were unmolded, and each cube was placed in a sealable plastic bag. The samples were then allowed to cure at 70 °F and 90 to 100 percent relative humidity until they were tested.

The molds for this procedure were stainless steel cubes, 2 in on each side, that come in a set of three cubes per mold. Before the mix was poured, the molds were coated with mineral oil to facilitate unmolding of the samples. The samples were prepared by mixing the components to the specified ratios and

pouring the results into 15 to 18 cubes at one time. Most samples were tamped into the molds following the procedures of ASTM C 109-86. The samples S/Sd with portland cement were too stiff to allow this. They were tamped into the molds using a drop hammer developed by the U.S. Army Corps of Engineers Waterways Experimental Station for this purpose.[4]

To avoid possible sample contamination by the metal of the molds and the release agents, separate samples from each pour were taken for chemical analysis. A representative part of the mixture was placed into a clean glass container, closed with a Teflon-lined lid, and shipped periodically during the program to the appropriate laboratory for analysis. While ideally the analyses should have been performed when the UCS tests were run on the 14th and 28th days, the laboratory scheduling did not always allow this.

The mixing schedule was set up so that on each day, one SARM and one binder were mixed at three different binder-to-SARM (B/S) ratios. For example samples 16, 17, and 18 were prepared on the same day. These were SARM II S/Sd with kiln dust at B/S ratios of 1:1, 2:1, and 3:1, respectively. The ratios used were determined by the procedure described in section 3.2. The mixing and molding procedures are described in section 3.3. Then on September 14, 21, and 28 and on October 5 (7, 14, 21 and 28 days after mixing), three cubes of each sample were subjected to the UCS. On the 14th and 28th days, the results of the UCS were:

Sample	14-day UCS (psi)	28-day UCS (psi)
16	60	85
17	190	216
18	225	252

For this particular SARM/binder mix, the 2:1 B/S ratio (sample 16) resulted in a product that had a UCS which was minimally above 50 psi. Therefore, first thing on the morning of the 14th and 28th days when the UCS tests were completed, the results were relayed by telephone to the laboratories performing the TCLP and TWA tests. In this case, they were told to analyze sample 16 and not analyze samples 17 and 18. All the samples had been sent to the laboratories in the glass jars and had been received by the analytical laboratories prior to these days, as described in section 3.3. This procedure was repeated for each set of samples.

Note that in a few cases, different B/S ratios satisfied the UCS criteria at the 14th and 28th days. For example, sample 30 satisfied the UCS criteria after 14 days of curing while sample 29 satisfied them after 28 days.

3.4 MONITORING OF VOLATILE ORGANIC COMPONENTS

The volatile emissions from the curing samples were checked by withdrawing a gas sample from the polyethylene bag that they were stored in and analyzing the gas with a gas chromatograph equipped with a flame

ionization detector (GC/FID). The samples were tested on the 14th and 28th days to determine whether the level of volatile emissions had changed during the curing process. The gas sample was withdrawn from the sealed bag that the sample was stored in and injected into the GC immediately. A 5-mL sample was taken in each case, and the results were compared to liquid standards of the volatile compounds.

The following conditions were used for the GC/FID: 30-mL/min Helium flow through the 30-m DB-5 megabore column. The injector and detector temperatures were set at 280 °C and 300 °C, respectively. The temperature program was 40 °C for 7 min, ramping at 20 °C/min to 270 °C, and holding for 4 min. This temperature program adequately separated the volatile compounds of interest.

3.5 MIXING PROCEDURE

Previous studies and ongoing work conducted by Acurex Corporation for EPA (Contract 68-02-3993, Work Directives 32 and 37) have shown that a large portion of any volatile components in the waste is released to the air while mixing with stabilizing agents. Therefore, a sealed mixing system (see figure 3-1) was devised to mix the components for these tests. It consisted of a framework that held up to three 1-gal "paint cans" on a shaft that rotated them end-over-end. This tumbling action mixed the contents. The dry components for each of the samples were weighed into the cans, and, just before placement in the mixer, the mixing was allowed to take place for as long as desired. One hour was found to be adequate to make a homogeneous mixture.

This mixing system worked well for mixing all the samples solidified with portland cement. Those samples using lime or lime kiln dust released gas during mixing and increased the temperature to such a level that they could not be mixed in a closed system; there would have been a danger of explosion. As a result, these samples were prepared in open containers and mixed by hand. It is recognized that this procedure resulted in a greater loss of volatile and semivolatile components but that it was an unavoidable necessity.

3.6 DETERMINATION OF MATRIX STRENGTH

The samples obtained by the procedures described above were subjected to unconfined compressive strength (UCS) tests described in ASTM C 109-86. Triplicate samples were tested at 7, 14, 21, and 28 days after curing, also according to method ASTM C 109-86.

On each of the above four days, three cubes were selected at random from each mixture. The surface area of each cube was accurately determined by micrometer measurements of its dimensions. Each cube was then subjected to uniform increments of pressure in a UCS apparatus until it broke. The breaking pressure was recorded. The unconfined compressive strength was calculated by dividing the force required to break the cube by the area (approximately 4 in^2, 6.45 cm^2) over which the force was spread. The results are triplicate measurements for each SARM, binder, and B/S ratio.

3.7 TCLP AND TWA TESTS

As discussed in section 3.3, whenever a mixture was molded, a portion of the same mass was placed into glass jars. The jars were periodically shipped to a laboratory where the contents were subjected to TWA, to determine the amount of each of the contaminants in the SARM, and to TCLP to determine the amount of these contaminants that would leach using this standard procedure. These tests were conducted on samples at 14 and 28 days after mixing, although it should be noted that deviations from this schedule occurred for the TWAs because of laboratory scheduling. The results of the TWA are presented in appendix A and of the TCLP in appendix B.

Not all the samples subjected to the UCS were also subjected to the chemical analyses. The protocol for this program required that only those mixtures that resulted in a product which at 14 and 28 days after mixing satisfied the following criteria would be subjected to these two chemical analyses.

1. A UCS which was minimally above 50 psi

2. If the UCS for all mixtures of a given blend did not achieve a UCS greater than 50 psi, that one showing the highest value was subjected to the analyses

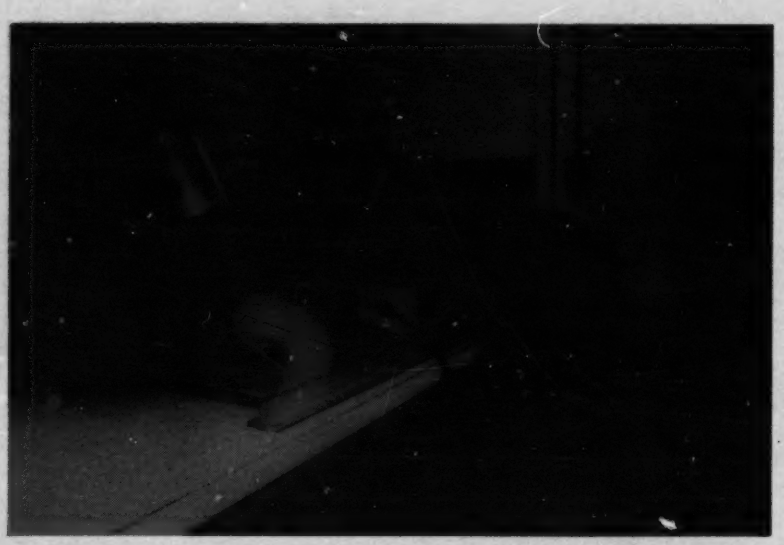

Figure 3-1. Sealed Mixing Apparatus

SECTION 4

DISCUSSION OF RESULTS

The first tests under this program were conducted to determine the amount of binder and water that was required to achieve an acceptable product. Because these tests were used to design the main portion of the program, the results are discussed in section 3.2. The major conclusion that can be drawn from them is that SARMs require a large amount of binder and water to form a hard, monolithic mass. It was found that roughly equal parts of binder and SARM were required to get signs of setting up in 24 to 48 h. The portland cement consistently provided the products with the highest UCS and CP hardness and the most rapid (within a few hours) setup time. The UCS test results are discussed further in section 4.1.

The other useful piece of information which resulted from the preliminary tests was that the total solids content of a waste may be a better indication of the amount of water needed to harden it than the normally used water-to-binder (W/B) ratio. In virtually all cases tested, a water-to-total-solids (W/TS) ratio in the 0.4 range resulted in a monolithic mass. It is recommended that other data be examined to see if this observation is unique to the systems studied here or if it can be applied to other S/S processes and wastes.

The organic emissions from the S/Sd SARMs were measured during the course of this experiment. These measurements were highly qualitative; however, they did not appear to indicate that S/S with the binders tested reduced air emissions. This is consistent with other data available in the literature. These measurements are discussed in section 4.2.

The final set of data that needs to be discussed is the results of the TWA and TCLP evaluations of the untreated and S/Sd SARMs. One of the goals of this work was the determination of a correlation between the UCS and reduction in the TCLP. The results did not indicate that this type of correlation exists. S/S clearly reduced the leaching of the metals as measured by the TCLP especially with portland cement as the binder.

The TWA results did not lend themselves to evaluation. In principle, the TWA is not actually an indication of how well the contaminants are fixed by a given process; rather, it indicates whether a given analyte is removed from the waste, chemically converted to another compound, or bound to an inert matrix so tightly that even grinding and extraction with solvents would not remove it. In this case, after allowing for dilution by the binders and water, the amount of metal in the SARMs appeared to actually increase for most of the samples. The TWA results are discussed in section 4-4.

4.1 UNCONFINED COMPRESSIVE STRENGTH

The UCS tests were conducted on three samples or cubes of each SARM/binder type and ratio. The results of each of the tests are given in appendix C, table C-1, and in figures C-1 through C-6. As can be seen, the results show little variation in the UCS values for each replicate. This gives a preliminary indication that the mixing of the SARM, binder, and water was thorough. The UCS is sensitive to inhomogeneity in the mixture.

The three measurements of the UCS taken on the same mixture were averaged. The mean for each condition is given in table 4-1, which also gives the component concentration for each sample, the date mixed, and binder type. To facilitate evaluation of the results, table 4-1 duplicates key information from other experiments, such as the W/TS ratio and B/S ratio.

When the testing was first started, the samples S/Sd with portland cement proved to be too strong to test on the available UCS apparatus after 7 days of curing. To get a UCS reading, it was necessary to ship these samples to the Environmental Protection Agency in Cincinnati, which used the facilities at the University of Cincinnati to test samples 1 through 12. The UCS tests on these samples were only done at 14 and 28 days because of shipping delays and equipment scheduling constraints.

The UCS of these samples proved also to exceed the range of the equipment available at the University of Cincinnati. It was therefore decided that because all samples (except for one set which apparently did not set up well) exceeded the minimum required UCS (50 psi), the minimum B/S ratio samples would be subjected to the TCLP and TWA. It is worth noting that a few samples proved to have a substantially lower UCS than the majority of the portland cement set. This can be explained by the fact that a sealed mixing apparatus was used to mix these samples. As discussed earlier, the samples using lime kiln dust and lime/flyash as binders could not be mixed in the sealed system and had to be mixed by hand. The sealed system, therefore, while providing adequate mixing, did not do as thorough a job as did hand mixing.

The results of the UCS tests are presented in appendix C and summarized in table 4-1. Table C-1 in appendix C gives the results of each UCS test, consisting of three cubes. The mean of these three measurements is defined as the UCS value for that mixture of SARM and binder. Table 4-1 shows the means of the UCS as well as the ratios of water, binder, and SARM (also called soil) that was used in the preparation of each sample. Figures C-1 through C-6 in appendix C are graphical representations of the mean UCS versus time for each mixture. They illustrate how this value varied at fixed B/S ratios versus days-after-mixing for each SARM. As discussed above, the UCS for those SARMs S/Sd with portland cement exceeded 1000 psi by the 14th day. They certainly exceeded the 50-psi value within a few hours of mixing.

The lime kiln dust appeared to make a softer product than did the portland cement. This may be due to interference from the contaminants in the SARM or simply to the fact that curing required more than 30 days. The trends show the product continually hardening. This is to be expected, as lime kiln dust will cure slowly as it absorbs carbon dioxide from the air.

TABLE 4-1. MIX RATIOS AND RESULTS OF UCS TESTS FOR EACH SAMPLE SET,

Sample Number	SARM Type	Binder Type	B/S Ratio	W/TS Ratio	Days After Mixing 7	14	21	28
1	I	PORTLAND	0.7	0.40	NA	977	NA	>1000
2	I	CEMENT	1.2	0.40	NA	>1000	NA	>1000
3	I	TYPE 1	2.3	0.40	NA	>1000	NA	>1000
4	II	PORTLAND	0.7	0.40	NA	>1000	NA	>1000
5	II	CEMENT	1.2	0.40	NA	>1000	NA	>1000
6	II	TYPE 1	2.3	0.40	NA	>1000	NA	>1000
7	III	PORTLAND	0.7	0.40	NA	28	NA	>1000
8	III	CEMENT	1.2	0.40	NA	99	NA	>1000
9	III	TYPE 1	2.3	0.40	NA	71	NA	>1000
10	IV	PORTLAND	0.7	0.40	NA	15.8	NA	16.2
11	IV	CEMENT	1.2	0.40	NA	167	NA	160
12	IV	TYPE 1	2.3	0.40	NA	177	NA	300
13	I	KILN	1	0.40	5	72.9	93	113
14	I	DUST	2	0.45	5	51.8	54	241
15	I		3	0.40	176	211	215	81.1
16	II	KILN	1	0.40	37.5	59.7	78.3	85.1
17	II	DUST	2	0.40	128	190	164	216
18	II		3	0.40	183	225	275	252
19	III	KILN	1	0.40	32.9	36.6	37.1	38.5
20	III	DUST	2	0.40	33	38.4	40.8	39
21	III		3	0.40	45.7	44.7	43.7	79.8
22	IV	KILN	1	0.42	27.9	28.1	26.8	32.2
23	IV	DUST	2	0.43	38.9	55.7	52.4	52.2
24	IV		3	0.40	35.7	38.2	33	40.1
25	I	LIME/	1	0.45	24.1	27.3	26	32.3
26	I	FLYASH	2	0.45	22.2	29	33.9	40.4
27	I		3	0.45	19.5	30.4	32.9	46.6
28	II	LIME/	1	0.45	9.9	17.1	17.3	28.8
29	II	FLYASH	2	0.48	17.2	24.2	26.9	62.4
30	II		3	0.49	19.4	31.4	41.2	73.4
31	III	LIME/	1	0.48	21.9	28.7	29.1	30.7
32	III	FLYASH	2	0.49	30.3	33	36.4	36.5
33	III		3	0.50	34.8	48.8	48.2	50.9
34	IV	LIME/	1	0.45	34.9	36	34.8	37.9
35	IV	FLYASH	2	0.40	29.8	38.7	36.3	40.5
36	IV		3	0.45	36.9	35.7	37.9	42.2

As discussed above, the UCS for the SARMs that were S/Sd with portland cement was very high within 1 day after mixing. Those SARMs S/Sd with kiln dust and lime/flyash were far weaker. Most of these SARM samples could not satisfy the 50-psi minimum after 7 days. Figures C-1 through C-6 in appendix C show the UCS values plotted against time. Interestingly, there is a small but pronounced trend upwards. That is, the solids were, in general, getting stronger with time. This is expected when using lime-based solidifying agents, which can take years to set up. No clear-cut trend was identified as to which SARM produced a stronger product.

Figure C-3 is interesting in that it first appears that SARM 1 and SARM 2 are S/Sd well by the kiln dust. Then on the 28th day, their strength appears to drop. No reason for this drop is apparent. It may be an artifact of the testing procedure or just due to random sample fluctuation. However, the data are consistent enough that this phenomenon may warrant further examination.

4.2 VOLATILE EMISSIONS

The organic volatile and semivolatile emissions from the S/Sd SARM soil samples were qualitatively made to track the loss of organic components from the samples into the surrounding air. After curing overnight, the SARM samples were placed into polyethylene bags and sealed until tested for UCS. At 14 and 28 days, a 5-mL sample of the air in each bag of SARM sample was withdrawn for analysis before the bag was opened and the cube measured. The gas sample was injected onto a gas chromatograph to determine which compounds were present. It should be noted that this methodology only gave concentration for the compounds in the headspace. Because no gas flux measurements through the plastic bags were made, these tests cannot be used to calculate the emission rate of the organics. Because of this limitation of the experiment, there was no value to measure the concentrations to a high level of precision. As a result, they should be construed as qualitative in nature. Table 4-2 shows the concentrations of each of the added organic compounds in the headspace, expressed in milligrams per liter (mg/L) of air at 14 and 28 days after mixing.

Other research being conducted in parallel to this program has shown that S/S with the agents used here does not significantly reduce the rate of release of volatile organics to the atmosphere.[2] The headspace concentration of the organic compounds was measured here to confirm this observation. The organic concentration in the polyethylene bag varied in a random manner throughout the program. While a slow drop in the concentration seemed to occur, this trend was not definite.

The plastic bags used to store the samples were made of light duty polyethylene and, while equipped with a "zip lock," were not airtight. Because air (or at least the carbon dioxide in the air) is necessary to cure the lime and lime kiln dust-based solidifying agents, sealing the samples completely would have slowed the curing process. In addition, the temperature changes and off gassing from the curing process often caused the bag seals to open by themselves. The S/Sd SARM samples continued to lose the volatile and organic compounds to the air, which would eventually have been depleted.

TABLE 4-2. RESULTS OF HEAD-SPACE ANALYSES

(SARM) SAMPLE NO.	BINDER	HEADSPACE CONCENTRATION AT 14 AND 28 DAYS (ppm)									
		ACT	CLB	DCE	ETB	STY	TCE	XYL	ANT	BEP	PCP
I	1 PC	90	40	19	560	38	51	1311	31	1	2
	1 PC	10	23	18	380	23	37	909	21	2	5
	2 PC	772	24	13	357	21	34	719	21	1	4
	2 PC	11	10	13	167	1	18	188	12	ND	3
	3 PC	531	16	5	249	ND	ND	541	18	1	ND
	3 PC	31	8	12	151	11	15	370	8	ND	4
II	4 PC	10	ND	ND	18	1	ND	47	3	1	ND
	4 PC	7	ND	ND	15	1	11	36	2	ND	4
	5 PC	3	ND	ND	ND	ND	ND	12	3	ND	ND
	5 PC	3	ND	ND	11	ND	11	31	2	ND	3
	6 PC	11	ND	ND	35	3	ND	91	3	1	ND
	6 PC	5	ND	ND	ND	ND	ND	8	2	1	3
III	7 PC	2	ND	ND	22	2	ND	56	1	4	ND
	7 PC	2	ND	ND	11	ND	ND	29	1	1	6
	8 PC	6	7	ND	77	7	ND	215	3	ND	ND
	8 PC	2	ND	ND	ND	ND	ND	6	2	ND	5
	9 PC	3	5	ND	67	6	ND	187	4	ND	ND
	9 PC	5	ND	ND	ND	ND	ND	7	2	ND	3
IV	10 PC	47	ND	ND	34	2	ND	78	1	1	1
	10 PC	9	ND	7	30	ND	ND	68	1	ND	3
	11 PC	55	2	ND	22	1	ND	51	ND	ND	ND
	11 PC	5	ND	ND	37	ND	ND	78	1	ND	2
	12 PC	6	ND	ND	9	1	ND	21	ND	ND	ND
	12 PC	40	ND	ND	62	3	ND	125	3	ND	ND
I	13 KD	7	ND	6	13	ND	ND	30	ND	ND	3
	13 KD	3	ND	ND	56	4	ND	143	2	ND	7
	14 KD	4	ND	ND	ND	ND	ND	ND	ND	ND	ND
	14 KD	13	ND	ND	ND	ND	ND	ND	4	ND	3
	15 KD	22	ND	ND	ND	ND	ND	ND	6	ND	2
	15 KD	2	ND	ND	13	ND	10	35	4	ND	5
II	16 KD	9	ND	ND	ND	ND	ND	ND	2	ND	4
	16 KD	5	ND	ND	ND	ND	ND	ND	3	ND	3
	17 KD	5	ND	ND	ND	ND	ND	ND	1	ND	4
	17 KD	2	ND	ND	ND	ND	ND	6	ND	ND	ND
	18 KD	1	ND	ND	ND	ND	ND	8	1	ND	ND
	18 KD	1	ND	2	7	ND	ND	19	3	ND	ND

continued

TABLE 4-2. concluded

(SARM) SAMPLE NO. BINDER	HEADSPACE CONCENTRATION AT 14 AND 28 DAYS (ppm)									
	ACT	CLB	DCE	ETB	STY	TCE	XYL	ANT	BEP	PCP
III 19 KD	1	ND	ND	ND	ND	ND	5	1	ND	ND
19 KD	ND	ND	ND	ND	ND	ND	4	1	ND	7
20 KD	ND	ND	ND	ND	ND	ND	8	1	ND	9
20 KD	1	ND	ND	ND	ND	ND	5	1	ND	3
21 KD	1	ND	ND	9	ND	ND	24	2	ND	6
21 KD	ND	ND	ND	ND	ND	ND	6	3	1	4
IV 22 KD	12	ND	5	12	ND	ND	33	4	ND	2
22 KD	ND	ND	3	ND	ND	ND	8	12	ND	ND
23 KD	35	ND	ND	4	ND	ND	12	3	5	ND
23 KD	1	ND	15	19	ND	9	52	10	ND	3
24 KD	36	ND	ND	30	3	ND	103	5	1	4
24 KD	ND	ND	2	ND	ND	ND	7	5	ND	ND
I 25 LF	115	11	17	163	12	37	357	1	1	6
25 LF	18	15	15	239	12	44	525	3	ND	ND
26 LF	172	16	20	296	12	61	633	1	ND	8
26 LF	5	11	11	213	10	42	491	4	ND	ND
27 LF	157	22	25	410	2	73	842	3	2	13
27 LF	21	18	41	265	12	54	556	5	4	3
II 28 LF	12	ND	ND	9	ND	ND	25	1	2	12
28 LF	1	ND	ND	ND	ND	ND	8	1	ND	5
29 LF	3	ND	ND	ND	ND	ND	3	ND	ND	2
29 LF	ND	ND	5	8	ND	ND	22	1	ND	ND
30 LF	3	ND	ND	6	ND	ND	16	ND	ND	7
30 LF	ND	ND	ND	ND	ND	ND	7	1	ND	ND
III 31 LF	7	3	14	9	ND	ND	26	1	1	4
31 LF	2	ND	6	1	ND	ND	4	5	10	ND
32 LF	4	ND	5	ND	ND	ND	ND	1	ND	ND
32 LF	2	ND	ND	1	ND	ND	5	2	5	3
33 LF	1	ND	ND	1	ND	ND	6	2	ND	ND
33 LF	1	ND	ND	5	ND	ND	13	2	3	ND
IV 34 LF	23	ND	25	148	9	18	375	2	1	ND
34 LF	12	8	ND	ND	ND	ND	6	7	ND	11
35 LF	39	ND	21	20	3	ND	76	10	ND	ND
35 LF	4	ND	ND	ND	ND	ND	4	9	ND	ND
36 LF	5	ND	17	49	4	ND	153	6	ND	ND
36 LF	1	ND	ND	1	ND	ND	3	7	ND	ND

ACT = acetone, CLB = chlorobenzene, DCE = 1,2-dichloroethane,
ETB = ethylbenzene, STY = styrene, TCE = tetrachloroethylene
XYL = xylene, ANT = anthracene BEP = bis(2-ethylhexyl)phthalate
ND = not detected PCP = pentachlorophenol
Note: First entry for each sample is concentration at 14 days, second is at 28 days

4.3 RESULTS OF TCLP ANALYSES

Samples of those mixes that had a UCS minimally greater than 50 psi or which showed the highest UCS below 50 psi after 14 and 28 days were subjected to Toxicity Characteristics Leaching Procedure (TCLP). The TCLP analysis was done by Lee Wan & Associates under EPA Contract No. 68-03-3393. The analyses were done using SW-846 methods.[5] the TCLP results for the metals are summarized in table 4-3. All of the results are presented in appendix B, tables B-1 through 12.

Table 4-3 shows the concentration of each metal found in the TCLP leachate of the raw SARMs (identified as RAW) and in SARMs I through IV S/Sd with portland cement (PC), lime kiln dust (KD), and lime-flyash (LF). The results are presented for samples at 14 and 28 days after mixing. For each metal, the first column lists the parts per million found in the TCLP extract, and the second column lists the percent reduction that occurred in the extract from the raw SARM to the S/Sd material. The percent reduction includes a correction for the dilution of the metals caused by the addition of the binders.

The tables in appendix B list the amount of each compound found at 14 days after mixing, 28 days after mixing, the apparent percent reduction, and the actual reduction. The apparent reduction is the value of the TCLP obtained after 28 days of curing subtracted from the TCLP of the original soil (not corrected for the dilution due to the solidifying agents) and divided by the latter value. It is multiplied by 100 to present the result as a percent.

The actual TCLP percent reduction is the same as the apparent reduction but corrected for the dilution of the SARM by the solidifying agent. It is otherwise calculated in the same manner as the apparent reduction. The calculation is described by the following equations:

$$TCLP_a = 100\% * (TCLP_o - TCLP_{28})/TCLP_o \quad (1)$$

$$TCLP_c = 100\% * (TCLP_o - TCLP_{28} * CF)/TCLP_o \quad (2)$$

where:

$TCLP_a$ = TCLP apparent
$TCLP_o$ = TCLP of the initial SARM
$TCLP_{28}$ = TCLP of the S/Sd SARM after 28 days
$TCLP_c$ = TCLP corrected for dilution
CF = Dilution correction factor from appendix B or C which is the sum of the weights of the SARM, binder and water used for a given sample divided by the weight of SARM

TABLE 4-3. SUMMARY OF TCLP RESULTS FOR METALS

(SARM) Sample No.	Binder (Day)	Arsenic a	Arsenic b	Cadmium a	Cadmium b	Chromium a	Chromium b	Copper a	Copper b	Lead a	Lead b	Nickel a	Nickel b	Zinc a	Zinc b
I	RAW	ND		0.53		ND		0.61		0.49		0.27		9.2	
1	PC(14)	ND	-	ND	100	0.06	+	0.07	81	0.15	75	0.04	70	0.23	96
14	KD(14)	ND	-	ND	100	0.06	+	0.04	81	ND	100	ND	100	0.27	94
27	LF(14)	ND	-	ND	100	0.02	+	0.03	98	ND	100	ND	100	0.14	94
1	PC(28)	ND	-	ND	100	0.06	+	0.06	83	0.15	75	0.04	70	0.49	91
15	KD(28)	ND	-	ND	100	0.09	+	0.03	98	ND	100	ND	100	0.62	73
27	LF(28)	ND	-	ND	100	0.02	+	0.03	98	ND	100	ND	100	ND	100
II	RAW	ND		0.73		ND		0.89		0.7		0.4		14.6	
4	PC(14)	ND	-	ND	100	0.03	+	0.04	92	0.15	82	0.04	83	0.09	99
16	KD(14)	ND	-	ND	100	0.08	+	0.07	79	0.44	+	ND	100	0.25	97
30	LF(14)	ND	-	ND	100	ND	-	ND	100	ND	100	ND	100	0.22	99
4	PC(28)	ND	-	ND	100	0.03	+	0.06	89	0.15	83	0.04	83	0.54	94
16	KD(28)	ND	-	ND	100	0.05	+	0.09	89	0.37	+	ND	100	0.78	89
29	LF(28)	ND		ND	100	ND	-	0.03	90	ND	100	ND	100	0.02	100
III	RAW	6.39		33.1		ND		80.7		19.9		17.5		359	
7	PC(14)	ND	100	ND	100	0.07	+	0.15	100	0.63	95	ND	100	0.58	100
21	KD(14)	ND	100	ND	100	0.22	+	1.02	96	13.3	+	ND	100	4.38	95
33	LF(14)	0.81	52	0.02	100	0.03	+	2.96	87	51	+	ND	100	3.81	96
7	PC(28)	ND	100	ND	100	0.07	+	0.09	100	ND	100	ND	100	0.69	100
21	KD(28)	0.21	98	ND	100	0.12	+	0.85	96	18.3	+	ND	100	4.07	95
33	LF(28)	0.79	51	0.02	100	0.07	+	2.59	87	51	+	0.03	99	3.97	96
IV	RAW	9.58		35.3		0.06		10		70.4		26.8		396	
10	PC(14)	ND	100	ND	100	0.06	+	0.14	100	0.39	99	ND	100	0.39	100
23	KD(14)	0.16	95	ND	100	0.11	+	1.88	97	12.4	43	ND	100	4.57	97
	LF(14)	1.61	50	ND	100	0.07	+	1.92	96	91.8	+	ND	100	3.22	96
10	PC(28)	ND	100	ND	100	0.06	+	0.17	100	0.37	99	ND	100	0.74	100
23	KD(28)	0.27	92	ND	100	0.12	+	1.67	97	21.4	9	ND	100	3.72	97
	LF(28)	0.98	59	0.02	100	0.07	+	2.18	95	65	+	ND	100	3.64	96
Detection Limit		0.15		0.01		0.01		0.02		0.15		0.04		0.01	

Notes: (a) TCLP results in ppm
(b) percent reduction, corrected for dilution

ND - below detection limit
+ - increase over raw SARM

To illustrate the use of this correction, consider the sample described in Table B-1. The lead in TCLP of the untreated SARM I was 0.49 ppm. The TCLP of the S/Sd sample at 28 days (as well as at 14 days) was 0.15 ppm. The dilution factor for the treatment was 1.7. That is, the TCLP corrected for the dilution of the SARM is in reality 1.7*0.15 = 0.255 ppm. Therefore the percent TCLP reduction corrected for dilution is:

100% * (0.49-0.255)/0.49 = 48%

Note that the results are given to the nearest percent in all cases since the TCLP results are usually only reproducible to two significant figures. Added significant figures in the results would imply a greater accuracy than exists.

Each part of the tables in appendix C also lists the description of the sample such as sample number, binder type, binder/soil ratio, density, the volume dilution factor, and the SARM type.

All the concentrations are reported in terms of the liquid extraction (milligrams per liter). These concentrations reflect a dilution of 20:1 over the original solid. This is consistent with SW-846.

The leaching for the TCLP must be performed using a buffered solution of specified pH. The samples submitted were highly caustic and may have overwhelmed the buffering capacity of the solution. Unfortunately, because the laboratory did not report the pH of the leaching solution, it is difficult to understand the underlying chemistry from these results. The portland cement and lime kiln dust used for this program had been analyzed for metals (by atomic absorption spectroscopy) under a different project.[2] The analyses had not shown the metals of interest present. It is possible that some of the metal analytes were present in the other binder components, the flyash and the lime.

4.4 RESULTS OF TWA ANALYSES

The Total Waste Analysis (TWA) was performed by Hittman Ebasco Associates under EPA Contract No. 68-01-7280. SW-846 methods were used in the extraction and analysis of the samples. The first set of samples (14 day) was extracted and analyzed in duplicate as a check on the homogeneity of the samples and the performance of the laboratory. The results of the analyses for the metals are presented in table 4-4. The full results are presented in appendix A, tables A-1 through 12.

Table 4-4 gives the parts per million of each metal found in both the raw and S/Sd SARMs. Because no reduction in these metals occurred, the percent reduction is not given. They are not corrected for dilution as presented here although the corrected values are given in the tables of appendix A. The tables in appendix A also list the amounts of the metal salts found, the organic analyses, and the percent reduction (or increase) at 14 and 28 days after mixing, the apparent percent reduction, and the actual reduction. The apparent reduction is the value of the TWA obtained after 28 days of curing

TABLE 4-4. SUMMARY OF TWA RESULTS, METALS

(SARM) SAMPLE NO.	BINDER (DAY)	TWA RESULTS (ppm) As	Cd	Cr	Cu	Pb	Ni	Zn
I	RAW	18	17	27	193	190	27	392
1	PC(14)	18	18	49	195	453	37	393
14	KD(14)	15	12	31	113	183	65	299
27	LF(14)	29	8	14	78	89	19	182
1	PC(28)	15	17	56	164	189	32	320
15	KD(28)	12	12	22	101	119	69	232
27	LF(28)	30	9	19	62	113	16	151
II	RAW	18	23	37	260	240	32	544
4	PC(14)	15	18	47	125	149	34	351
16	KD(14)	14	17	51	133	280	50	383
30	LF(14)	28	10	15	85	97	21	161
4	PC(28)	23	24	45	218	294	39	479
16	KD(28)	15	20	27	153	193	53	404
29	LF(28)	32	11	19	106	134	20	276
III	RAW	904	1,280	1,190	9,650	15,200	1,140	53,400
7	PC(14)	528	797	1,010	6,390	11,600	625	14,800
21	KD(14)	223	315	391	2,420	4,710	300	7,600
33	LF(14)	196	258	299	1,810	3,830	216	5,850
7	PC(28)	584	934	1,060	7,960	12,100	724	22,200
21	KD(28)	233	326	432	2,660	4,390	300	7,690
33	LF(28)	180	251	279	1,660	2,780	169	4,830
IV	RAW	810	1,430	1,650	13,300	16,900	1,380	28,900
10	PC(14)	506	858	1,060	7,040	12,100	616	17,500
23	KD(14)	290	541	550	4,230	6,320	418	11,200
35	LF(14)	281	448	461	4,440	6,590	374	9,890
10	PC(28)	563	952	1,020	10,100	8,680	753	21,000
23	KD(28)	271	490	516	4,860	5,190	449	12,300
36	LF(28)	225	306	386	3,430	4,590	255	7,020

subtracted from the TWA of the original soil, not corrected for the dilution due to the solidifying agents, and divided by the latter value. It is multiplied by 100 to present the result as a percent.

The actual TWA percent reduction is the same as the apparent reduction but corrected for the reduction of the TWA due to the simple dilution of the SARM by the solidifying agent. It is calculated in the same manner as the actual TCLP reduction was. Each part of the tables in appendix A also lists the description of the sample, such as sample number, binder type, B:S ratio, density, the dilution factor, and the SARM type.

The TWA analyses for the volatile organics showed the same pattern as the TCLP. The TWA analyses, however, showed the results magnified. That is, the S/Sd SARMs contained on the order of 80 to 90 percent fewer volatile organics than the original material. This is consistent with the hypothesis that the volatile organics were released to the air rather than trapped in the solid.

The TWA results for the semivolatile organics were unexpected. Stabilization appeared to result in an apparent increase in almost all the values. This was surprising as the semivolatile organics were present in all headspace samples. They were clearly being emitted during the mixing and curing process. This increase is most likely apparent rather than actual. It may well be an artifact of the analytical method. The TWA results appear to vary widely. The reason for this is unclear, but it may be due to the physical nature of the semivolatile compounds. They are heavy solids that go into solution slowly. As a result, the amount of each constituent in the liquid after the extraction for analysis may be more of a function of how much of the material actually dissolves than of the total amount of that compound in the waste. Under normal conditions, this error is not significant; however, in this case, the TWA values are corrected for dilution. This results in a "leveraging" of any error and a much higher degree of uncertainty for the TWA results.

The TWA results for the metals behaved similarly to that of the semivolatiles. Some metals showed large increases and some decreases. Once again, the problem was most likely due to the "leveraging" of any error by the dilution correction. Overall, the results showed no clear-cut increase or reduction in the TWA for the metals.

SECTION 5

QUALITY ASSURANCE/QUALITY CONTROL

The work done by Acurex under this program met the requirements of a Level 3 program as defined by the HWERL (Now RREL) QA manual.[7] The measurement of the TWA and TCLP was performed under separate tasks with EPA. The QA/QC for these tasks was covered by another Quality Assurance Program Plan (QAPP). Data quality objectives for this program were determined prior to its start and agreed to by the parties in the QAPP based on expected performance of the systems and equipment used for the measurements as determined by experience and manufacturers' specifications. They are listed in table 5-1. All objectives were met.

5.1 DATA QUALITY FOR CRITICAL MEASUREMENTS

This project was designed to measure the leaching performance of synthetically contaminated soils from Superfund sites that have been S/Sd using specified commonly used techniques. The actual leaching performance of the samples was determined by the TCLP and TWA tests that were performed under two other project tasks. These TCLP and TWA measurements are not covered by the quality assurance project plan (QAPP) for this project. This project was responsible for mixing the materials (which were provided by EPA), performing routine tests on the resultant samples, and sending selected samples to the other laboratories for TCLP and TWA.

The semivolatile emissions were measured qualitatively. No quantification of these was necessary since this was not a major objective of the study. The elution time for each of the components selected was determined by the daily injection into the GC/FID of solutions of each component in a suitable solvent.

The ancillary measurements performed under this project were made using extremely stable, reliable devices. The thermometers were all mercury-in-glass and were accurate to within ± 0.5 °C. The relative humidity was measured by a wet-bulb/dry-bulb sling psychrometer, which is the primary standard for this measurement.

5.2 CALIBRATION

The major tests that were performed under this program were the UCS and CP tests. The CP is a rugged device designed for field use, which measures the force required to push a cone into a sample. It is calibrated by simply

TABLE 5-1. QA OBJECTIVES FOR PRECISION, ACCURACY, AND COMPLETENESS

Measurement	Method	Accuracy	Precision	Completeness
Penetration resistance	Cone Penetrometer	±10%	±10%	90%
Unconfined compressive strength	UCS tester	±10%	±10%	90%
Semivolatiles analysis	GC/FID	Qual.	Qual.	90%
Weight	Laboratory Balance	±5%	±5%	90%
Temperature	Thermometer	±1°C	±1°C	90%
Relative Humidity	Sling Psychrometer	±5%	±10%	90%

pushing it down against a scale and comparing the force it records against that of the scales. The compression testing machine used for the UCS measurements was an ASTM standard device in its own right. Cube dimensions were determined using standard machinist calipers that were purchased for the project and had been calibrated by the manufacturer.

The semivolatile emissions were measured qualitatively. A quantitative measure of the emissions was considered unnecessary for the scope of this study. The elution time for each of the components selected was determined by the daily injection of solutions of each component.

The GC is the only instrument used which is susceptible to drift and other variation. Because of such instability, its performance on the standards was checked by daily monitoring of the elution times for the desired components. Because surrogate wastes of known composition were used, sample spikes for positive peak identification were unnecessary.

5.3 SAMPLING PROCEDURE

The only sampling activity that took place was the collection of the semivolatile emission sample for the GC analysis. This was performed in accordance with EPA Method 18, "Measurement of Gaseous Organic Compound Emissions by Gas Chromatography."

5.4 SAMPLE CUSTODY AND LABELING

Upon receipt, the soil samples were labeled and logged in according to the type of SARM, date received, receiving technician, and other pertinent information. Every time a portion of the sample was taken for testing or the sample was otherwise handled, an appropriate entry was made in the log. This included the amount removed or replaced, the responsible technician, date of the activity, soil destination or source, and any other pertinent comments. Each entry was signed by the person performing the activity. This log forms the "chain-of-custody" document for all samples held at Acurex Corporation.

The chain-of-custody was maintained with all samples sent to the analytical laboratories or other entities for further work.

SECTION 6

REFERENCES

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3. U.S. Army Corps of Engineers. Cone Penetrometer (CP) Use Manual. Army Document No. TM-5-530. Section XV.

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6. PEI Associates, Inc. CERCLA BDAT SARM Preparation and Physical Soils Washing Removal Efficiencies. Final Report. Contract 68-03-3413, Work Assignment No. 0-7. Prepared for EPA Hazardous Waste Engineering Research Laboratory. 1987.

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APPENDIX A

RESULTS OF TOTAL WASTE ANALYSES (TWA) OF SOLIDIFIED SARMS

TABLE A-1

TWA RESULTS FOR SARMS

SARM I BINDER - PORTLAND CEMENT CONCENTRATIONS IN MG/KG		14 DAY	28 DAY
	SAMPLE #	1	1
	SOIL/BINDER RATIO	1:0.7	1:0.7
	DILUTION FACTOR	1.7	1.7
	DENSITY g/cm^3	2.07	2.07

CONTAMINANT	TWA RAW SARM	TWA @ 14 DAY	TWA @ 28 DAY	% REDUCTION APPARENT	% REDUCTION ACTUAL
VOLATILES					
ACETONE	3150	710	560	82	70
CHLOROBENZENE	330	110	95	71	51
1,2-DICHLOROETHANE	380	16	11	97	95
ETHYLBENZENE	3350	1000	940	72	52
STYRENE	710	240	220	69	47
TETRACHLOROETHYLENE	600	110	84	86	76
XYLENE	4150	1500	1400	66	43
SEMIVOLATILE					
ANTHRACENE	940	860	930	1	-68
BIS(2-ETHYLHEXYL)PHTHALATE	600	820	630	-5	-79
PENTACHLOROPHENOL	135	58	50	63	37
INORGANIC (METALS)					
ARSENIC	18	18	15	17	-42
CADMIUM	17	18	17	0	-70
CHROMIUM	27	49	56	-107	-253
COPPER	193	195	164	15	-44
LEAD	190	453	189	1	-69
NICKEL	27	37	32	-19	-101
ZINC	392	393	320	18	-39

TABLE A-2

TWA RESULTS FOR SARMS

SARM II
BINDER - PORTLAND CEMENT
CONCENTRATIONS IN MG/KG

	14 DAY	28 DAY
SAMPLE #	4	4
SOIL/BINDER RATIO	1:0.7	1:0.7
DILUTION FACTOR	1.7	1.7
DENSITY G/CM³	1.92	1.92

CONTAMINANT	TWA RAW SARM	TWA @ 14 DAY	TWA @ 28 DAY	% REDUCTION APPARENT	% REDUCTION ACTUAL
VOLATILES					
ACETONE	230	68	250	-9	-85
CHLOROBENZENE	9.2	3	0.9	90	83
1,2-DICHLOROETHANE	3.9	ND	ND	100	100
ETHYLBENZENE	74	31	5.3	93	88
STYRENE	26	7.3	1.8	93	88
TETRACHLOROETHYLENE	16	3.3	ND	100	100
XYLENE	210	49	11	95	91
SEMIVOLATILE					
ANTHRACENE	275	150	150	45	7
BIS(2-ETHYLHEXYL)PHTHALATE	34	43	41	-21	-105
PENTACHLOROPHENOL	62	63	50	19	-37
INORGANIC (METALS)					
ARSENIC	18	15	23	-28	-117
CADMIUM	23	18	24	-4	-77
CHROMIUM	37	47	45	-22	-107
COPPER	260	125	218	16	-43
LEAD	240	149	294	-23	-108
NICKEL	32	34	39	-22	-107
ZINC	544	351	479	12	-50

TABLE A-3

TWA RESULTS FOR SARMS

		14 DAY	28 DAY
SARM III	SAMPLE #	7	7
BINDER - PORTLAND CEMENT	SOIL/BINDER RATIO	1:0.7	1:0.7
CONCENTRATIONS IN MG/KG	DILUTION FACTOR	1.7	1.7
	DENSITY g/cm³	1.92	1.92

CONTAMINANT	TWA RAW SARM	TWA @ 14 DAY	TWA @ 28 DAY	% REDUCTION APPARENT	% REDUCTION ACTUAL
VOLATILES					
ACETONE	220	150	150	32	-16
CHLOROBENZENE	8.9	5.4	2.6	71	50
1,2-DICHLOROETHANE	3.1	1.4	0.7	77	62
ETHYLBENZENE	100	63	34	66	42
STYRENE	24	14	8.7	64	38
TETRACHLOROETHYLENE	13	6.4	2.7	79	65
XYLENE	150	100	59	61	33
SEMIVOLATILES					
ANTHRACENE	265	340	450	-70	-189
BIS(2-ETHYLHEXYL)PHTHALATE	140	140	220	-57	-167
PENTACHLOROPHENOL	15	66	48	-220	-444
INORGANICS (METALS)					
ARSENIC	904	528	584	35	-10
CADMIUM	1280	797	934	27	-24
CHROMIUM	1190	1010	1060	11	-51
COPPER	9650	6390	7960	18	-40
LEAD	15200	11600	12100	20	-35
NICKEL	1140	625	724	36	-8
ZINC	53400	14800	2200	58	29

TABLE A-4

TWA RESULTS FOR SARMS

		14 DAY	28 DAY
SARM IV	SAMPLE #	10	10
BINDER - PORTLAND CEMENT	SOIL/BINDER RATIO	1:0.7	1:0.7
CONCENTRATIONS IN MG/KG	DILUTION FACTOR	1.7	1.7
	DENSITY g/cm^3	1.83	1.83

CONTAMINANT	TWA RAW SARM	TWA @ 14 DAY	TWA @ 28 DAY	% REDUCTION APPARENT	% REDUCTION ACTUAL
VOLATILES					
ACETONE	13000	550	1500	88	80
CHLOROBENZENE	270	66	150	44	6
1,2-DICHLOROETHANE	830	25	33	96	93
ETHYLBENZENE	2500	690	1600	36	-9
STYRENE	540	150	350	35	-10
TETRACHLOROETHYLENE	540	89	180	67	43
XYLENE	3700	970	2300	38	-6
SEMIVOLATILE					
ANTHRACENE	775	730	1200	-55	-163
BIS(2-ETHYLHEXYL)PHTHALATE	500	500	670	-34	-128
PENTACHLOROPHENOL	78	63	49	37	-7
INORGANIC (METALS)					
ARSENIC	810	506	563	30	-18
CADMIUM	1430	858	952	33	-13
CHROMIUM	1650	1060	1020	38	-5
COPPER	13300	7040	10100	24	-29
LEAD	16900	12100	8680	49	13
NICKEL	1380	616	753	45	7
ZINC	28900	17500	21000	27	-24

TABLE A-5

TWA RESULTS FOR SARMS

		14 DAY	28 DAY
SARM I	SAMPLE #	14	15
BINDER - KILN DUST	SOIL/BINDER RATIO	1:2	1:3
CONCENTRATIONS IN MG/KG	DILUTION FACTOR	3	4
	DENSITY g/cm^3	1.75	1.88

CONTAMINANT	TWA RAW SARM	TWA @ 14 DAY	TWA @ 28 DAY	% REDUCTION APPARENT	% REDUCTION ACTUAL
VOLATILES					
ACETONE	3150	79	120	96	85
CHLOROBENZENE	330	1.5	7.3	98	91
1,2-DICHLOROETHANE	380	0.8	7.3	98	92
ETHYLBENZENE	3350	19	8.3	100	99
STYRENE	710	4.3	5.6	99	97
TETRACHLOROETHYLENE	600	1.5	7.3	99	95
XYLENE	4150	30	20	100	98
SEMIVOLATILE					
ANTHRACENE	940	670	520	45	-121
BIS(2-ETHYLHEXYL)PHTHALATE	600	410	230	62	-53
PENTACHLOROPHENOL	135	640	50	63	-48
INORGANIC (METALS)					
ARSENIC	18	15	12	33	-167
CADMIUM	17	12	12	29	-182
CHROMIUM	27	31	22	19	-226
COPPER	193	113	101	48	-109
LEAD	190	183	119	37	-151
NICKEL	27	65	69	-156	-922
ZINC	392	299	232	41	-137

TABLE A-6

TWA RESULTS FOR SARMS

		14 DAY	28 DAY
SARM II			
BINDER - KILN DUST	SAMPLE #	16	16
CONCENTRATIONS IN MG/KG	SOIL/BINDER RATIO	1:1	1:1
	DILUTION FACTOR	2	2
	DENSITY g/cm^3	1.77	1.77

CONTAMINANT	TWA RAW SARM	TWA @ 14 DAY	TWA @ 28 DAY	% REDUCTION APPARENT	% REDUCTION ACTUAL
VOLATILES					
ACETONE	230	55	4.2	98	96
CHLOROBENZENE	9.2	0.1	0.006	100	100
1,2-DICHLOROETHANE	3.9	0.02	0.017	100	99
ETHYLBENZENE	74	0.8	0.03	100	100
STYRENE	26	0.4	0.02	100	100
TETRACHLOROETHYLENE	16	ND	ND	100	100
XYLENE	210	1.9	0.08	100	100
SEMIVOLATILE					
ANTHRACENE	275	170	140	49	-2
BIS(2-ETHYLHEXYL)PHTHALATE	34	42	28	18	-65
PENTACHLOROPHENOL	62	63	49	21	-58
INORGANICS (METALS)					
ARSENIC	18	14	15	17	-67
CADMIUM	23	17	20	13	-74
CHROMIUM	37	51	27	27	-46
COPPER	260	133	153	41	-18
LEAD	240	280	193	20	-61
NICKEL	32	50	53	-66	-231
ZINC	544	383	404	26	-49

TABLE A-7

TWA RESULTS FOR SARMS

		14 DAY	28 DAY
SARM III	SAMPLE #	21	21
BINDER - KILN DUST	SOIL/BINDER RATIO	1:3	1:3
CONCENTRATIONS IN MG/KG	DILUTION FACTOR	4	4
	DENSITY g/cm³	1.86	1.86

CONTAMINANT	TWA RAW SARM	TWA @ 14 DAY	TWA @ 28 DAY	% REDUCTION APPARENT	% REDUCTION ACTUAL
VOLATILES					
ACETONE	220	39	20	91	64
CHLOROBENZENE	8.9	0.03	0.19	98	91
1,2-DICHLOROETHANE	3.1	0.03	0.05	98	94
ETHYLBENZENE	100	0.16	2	98	92
STYRENE	24	0.11	0.79	97	87
TETRACHLOROETHYLENE	13	0.01	ND	100	100
XYLENE	150	0.38	4.2	97	89
SEMIVOLATILES					
ANTHRACENE	265	210	250	6	-277
BIS(2-ETHYLHEXYL)PHTHALATE	140	78	77	45	-120
PENTACHLOROPHENOL	15	600	62	-313	-1553
INORGANICS (METALS)					
ARSENIC	904	223	233	74	-3
CADMIUM	1280	315	326	75	-2
CHROMIUM	1190	391	432	64	-45
COPPER	9650	2420	2660	72	-10
LEAD	15200	4710	4390	71	-16
NICKEL	1140	300	308	73	-8
ZINC	53400	7600	7690	86	42

TABLE A-8

TWA RESULTS FOR SARMS

		14 DAY	28 DAY
SARM IV	SAMPLE #	23	23
BINDER - KILN DUST	SOIL/BINDER RATIO	1:2	1:2
CONCENTRATIONS IN MG/KG	DILUTION FACTOR	3	3
	DENSITY g/cm³	1.83	1.83

CONTAMINANT	TWA RAW SARM	TWA @ 14 DAY	TWA @ 28 DAY	% REDUCTION APPARENT	% REDUCTION ACTUAL
VOLATILES					
ACETONE	13000	410	180	99	96
CHLOROBENZENE	270	25	15	94	83
1,2-DICHLOROETHANE	830	1.6	8	99	97
ETHYLBENZENE	2500	270	170	93	80
STYRENE	540	69	45	92	75
TETRACHLOROETHYLENE	540	25	13	98	93
XYLENE	3700	410	260	93	79
SEMIVOLATILES					
ANTHRACENE	775	430	840	-8	-225
BIS(2-ETHYLHEXYL)PHTHALATE	500	330	590	-18	-254
PENTACHLOROPHENOL	78	62	64	18	-146
INORGANICS (METALS)					
ARSENIC	810	290	271	67	0
CADMIUM	1430	541	490	66	-3
CHROMIUM	1650	550	516	69	6
COPPER	13300	4230	4860	63	-10
LEAD	16900	6320	5190	69	8
NICKEL	1380	418	449	67	2
ZINC	28900	11200	12300	57	-28

TABLE A-9

TWA RESULTS FOR SARMS

		14 DAY	28 DAY
SARM I	SAMPLE #	27	27
BINDER - LIME/FLYASH	SOIL/BINDER RATIO	1:3	1:3
CONCENTRATIONS IN MG/KG	DILUTION FACTOR	4	4
	DENSITY g/cm^3	1.54	1.54

CONTAMINANT	TWA RAW SARM	TWA @ 14 DAY	TWA @ 28 DAY	% REDUCTION APPARENT	% REDUCTION ACTUAL
VOLATILES					
ACETONE	3150	1900	800	75	-2
CHLOROBENZENE	330	51	55	83	33
1,2-DICHLOROETHANE	380	12	9.6	97	90
ETHYLBENZENE	3350	440	700	79	16
STYRENE	710	100	150	79	15
TETRACHLOROETHYLENE	600	59	73	88	51
XYLENE	4150	660	960	77	7
SEMIVOLATILES					
ANTHRACENE	940	370	790	16	-236
BIS(2-ETHYLHEXYL)PHTHALATE	600	350	490	18	-227
PENTACHLOROPHENOL	135	70	710	-426	-2004
INORGANICS (METALS)					
ARSENIC	18	29	30	-67	-567
CADMIUM	17	8.4	8.5	50	-100
CHROMIUM	27	14	19	30	-181
COPPER	193	78	62	68	-28
LEAD	190	89	113	41	-138
NICKEL	27	19	16	41	-137
ZINC	392	182	151	61	-54

TABLE A-10

TWA RESULTS FOR SARMS

		14 DAY	28 DAY
SARM II	SAMPLE #	30	29
BINDER - LIME/FLYASH	SOIL/BINDER RATIO	1:3	1:2
CONCENTRATIONS IN MG/KG	DILUTION FACTOR	4	3
	DENSITY g/cm^3	1.59	1.56

CONTAMINANT	TWA RAW SARM	TWA @ 14 DAY	TWA @ 28 DAY	% REDUCTION APPARENT	% REDUCTION ACTUAL
VOLATILES					
ACETONE	230	13	57	75	26
CHLOROBENZENE	9.2	0.04	0.069	99	98
1,2-DICHLOROETHANE	3.9	0.012	0.11	97	92
ETHYLBENZENE	74	0.5	0.95	99	96
STYRENE	26	0.06	0.14	99	98
TETRACHLOROETHYLENE	16	0.024	0.033	100	99
XYLENE	210	0.89	1.8	99	97
SEMIVOLATILES					
ANTHRACENE	275	56	77	72	16
BIS(2-ETHYLHEXYL)PHTHALATE	34	12	12	65	-6
PENTACHLOROPHENOL	62	72	73	-18	-253
INORGANICS (METALS)					
ARSENIC	18	28	32	-78	-433
CADMIUM	23	9.6	11	52	-43
CHROMIUM	37	15	19	49	-54
COPPER	260	85	106	59	-22
LEAD	240	97	134	44	-68
NICKEL	32	21	20	38	-88
ZINC	544	161	276	49	-52

TABLE A-11

TWA RESULTS FOR SARMS

		14 DAY	28 DAY
SARM III	SAMPLE #	33	33
BINDER - LIME/FLYASH	SOIL/BINDER RATIO	1:3	1:3
CONCENTRATIONS IN MG/KG	DILUTION FACTOR	4	4
	DENSITY g/cm³	1.49	1.49

CONTAMINANT	TWA RAW SARM	TWA @ 14 DAY	TWA @ 28 DAY	% REDUCTION APPARENT	% REDUCTION ACTUAL
VOLATILES					
ACETONE	220	25	140	36	-155
CHLOROBENZENE	8.9	0.35	0.32	96	86
1,2-DICHLOROETHANE	3.1	0.23	0.2	94	74
ETHYLBENZENE	100	0.6	3.5	97	86
STYRENE	24	0.42	1.2	95	80
TETRACHLOROETHYLENE	13	0.29	0.22	98	93
XYLENE	150	2.9	7.9	95	79
SEMIVOLATILES					
ANTHRACENE	265	180	200	25	-202
BIS(2-ETHYLHEXYL)PHTHALATE	140	51	64	54	-83
PENTACHLOROPHENOL	15	73	69	-360	-1740
INORGANICS (METALS)					
ARSENIC	904	196	180	80	20
CADMIUM	1280	258	251	80	22
CHROMIUM	1190	299	279	77	6
COPPER	9650	1810	1660	83	31
LEAD	15200	3830	2780	82	27
NICKEL	1140	216	169	85	41
ZINC	53400	5850	4830	91	64

TABLE A-12

TWA RESULTS FOR SARMS

		14 DAY	28 DAY
SARM IV	SAMPLE #	35	36
BINDER - LIME/FLYASH	SOIL/BINDER RATIO	1:2	1:3
CONCENTRATIONS IN MG/KG	DILUTION FACTOR	3	4
	DENSITY g/cm^3	1.44	1.52

CONTAMINANT	TWA RAW SARM	TWA @ 14 DAY	TWA @ 28 DAY	% REDUCTION APPARENT	% REDUCTION ACTUAL
ACETONE	13000	1000	690	95	79
CHLOROBENZENE	270	110	43	84	36
1,2-DICHLOROETHANE	830	54	19	98	91
ETHYLBENZENE	2500	1100	730	71	-17
STYRENE	540	220	130	76	4
TETRACHLOROETHYLENE	540	140	66	88	51
XYLENE	3700	1600	920	75	1
SEMIVOLATILE					
ANTHRACENE	775	780	540	30	-179
BIS(2-ETHYLHEXYL)PHTHALATE	500	460	280	44	-124
PENTACHLOROPHENOL	78	73	68	13	-249
INORGANICS (METALS)					
ARSENIC	810	281	225	72	-11
CADMIUM	1430	448	306	79	14
CHROMIUM	1650	461	386	77	6
COPPER	13300	4440	3430	74	-3
LEAD	16900	6590	4590	73	-9
NICKEL	1380	374	255	82	26
ZINC	28900	9890	7020	76	3

APPENDIX B

RESULTS OF TOXICITY CHARACTERISTIC LEACHING PROCEDURE (TCLP) TESTS FOR SARMS

TABLE B-1

TCLP RESULTS FOR SARMs

SARM I
BINDER - PORTLAND CEMENT
CONCENTRATIONS IN mg/L EXTRACT

	14 DAY	28 DAY
SAMPLE #	1	1
SOIL/BINDER RATIO	1:0.7	1:0.7
DILUTION FACTOR	1.7	1.7
DENSITY g/cm³	2.07	2.07

UCS @ 7,14,21,28 DAY >250.....>250

CONTAMINANT	TCLP ACTUAL	TCLP @ 14 DAY	TCLP 28 DAY	% REDUCTION IN TCLP APPARENT	% REDUCTION IN TCLP ACTUAL
VOLATILES					
ACETONE	110	61	180	-64	-178
CHLOROBENZENE	5.2	2.39	1.32	75	57
1,2-DICHLOROETHANE	76	10	0.44	99	99
ETHYLBENZENE	27	6.28	10.3	62	35
STYRENE	9	5.84	2.78	69	47
TETRACHLOROETHYLENE	3.3	10	0.72	78	63
XYLENE	62	35	13.8	78	62
SEMIVOLATILES					
ANTHRACENE	2.6	0.02	0.03	99	98
BIS(2-ETHYLHEXYL)PHTHALATE	2.3	0.01	1.02	56	25
PENTACHLOROPHENOL	7.8	7	3.87	50	16
INORGANICS (METALS)					
	DET. LIM.				
ARSENIC	0.15	ND	ND	ND	—	—
CADMIUM	0.01	0.53	ND	ND	100	100
CHROMIUM	0.01	ND	0.06	0.06	—	—
COPPER	0.02	0.61	0.07	0.06	90	83
LEAD	0.15	0.49	0.15	0.15	69	48
NICKEL	0.04	0.27	0.04	0.04	85	75
ZINC	0.01	9.2	0.23	0.49	95	91

ND - BELOW DETECTION LIMIT

TABLE B-2

TCLP RESULTS FOR SARMs

SARM II
BINDER - PORTLAND CEMENT
CONCENTRATION IN mg/L EXTRACT

	14 DAY	28 DAY
SAMPLE #	4	4
SOIL/BINDER RATIO	1:0.7	1:0.7
DILUTION FACTOR	1.7	1.7
DENSITY g/cm³	1.92	1.92
UCS @ 7,14,21,28 DAY	>250.....>250	

CONTAMINANT	TCLP ACTUAL	TCLP @ 14 DAY	TCLP 28 DAY	% REDUCTION IN TCLP APPARENT	% REDUCTION IN TCLP ACTUAL
VOLATILES					
ACETONE	0.92	238	15	-1530	-2672
CHLOROBENZENE	0.05	2.4	0.17	-240	-478
1,2-DICHLOROETHANE	0.05	10	0.05	0	-70
ETHYLBENZENE	0.12	19.2	4.78	-3883	-6672
STYRENE	0.03	8.52	0.03	0	-70
TETRACHLOROETHYLENE	0.05	1.4	0.16	-220	-444
XYLENE	0.3	34.5	5.15	-1617	-2818
SEMIVOLATILES					
ANTHRACENE	0.01	0.02	0.01	0	-70
BIS(2-ETHYLHEXYL)PHTHALATE	0.22	0.01	0.09	59	30
PENTACHLOROPHENOL	0.9	0.41	0.11	88	79
INORGANICS (METALS)					
	DET. LIM.				
ARSENIC	0.15	ND	ND	ND	— —
CADMIUM	0.01	0.73	ND	ND	100 100
CHROMIUM	0.01	ND	0.03	0.03	— —
COPPER	0.02	0.89	0.04	0.06	93 89
LEAD	0.15	0.7	0.15	0.15	79 64
NICKEL	0.04	0.4	0.04	0.04	90 83
ZINC	0.01	14.6	0.09	0.54	96 94

ND - BELOW DETECTION LIMIT

TABLE B-3

TCLP RESULTS FOR SARMs

		14 DAY	28 DAY
SARM III	SAMPLE #	7	7
BINDER - PORTLAND CEMENT	SOIL/BINDER RATIO	1:0.7	1:0.7
CONCENTRATION IN mg/L EXTR	VOLUME DILUTION RATIO	1.7	1.7
	DENSITY g/cm^3	1.88	1.88
	UCS @ 7,14,21,28 DAY	>250.....>250	

CONTAMINANT	DET. LIM.	TCLP ACTUAL	TCLP @ 14 DAY	TCLP 28 DAY	% REDUCTION IN TCLP APPARENT	% REDUCTION IN TCLP ACTUAL
VOLATILES						
ACETONE		7.1	40.1	12.1	-70	-190
CHLOROBENZENE		0.38	0.08	0.01	97	96
1,2-DICHLOROETHANE		0.5	0.1	0.01	98	97
ETHYLBENZENE		4.6	1.67	0.21	95	92
STYRENE		0.5	0.6	0.02	96	93
TETRACHLOROETHYLENE		0.33	0.09	0.01	97	95
XYLENE		11	2.55	0.52	95	92
SEMIVOLATILES						
ANTHRACENE		0.01	0.01	0.02	-100	-240
BIS(2-ETHYLHEXYL)PHTHALATE		0.09	0.01	0.26	-189	-391
PENTACHLOROPHENOL		0.34	1.1	0.9	-165	-350
INORGANICS (METALS)						
ARSENIC	0.15	6.39	ND	ND	100	100
CADMIUM	0.01	33.1	ND	ND	100	100
CHROMIUM	0.01	ND	0.07	0.07	—	—
COPPER	0.02	80.7	0.15	0.09	100	100
LEAD	0.15	19.9	0.63	ND	100	100
NICKEL	0.04	17.5	ND	ND	100	100
ZINC	0.01	358.5	0.58	0.69	100	100

ND - BELOW DETECTION LIMIT

TABLE B-4

TCLP RESULTS FOR SARMs

		14 DAY	28 DAY
SARM IV	SAMPLE #	10	10
BINDER - PORTLAND CEMENT	SOIL/BINDER RATIO	1:0.7	1:0.7
CONCENTRATIONS IN mg/L EXT	DILUTION FACTOR	1.7	1.7
	DENSITY g/cm³	1.83	1.83
	UCS @ 7,14,21,28 DAY	250....	....>250

CONTAMINANT	DET. LIM.	TCLP ACTUAL	TCLP @ 14 DAY	TCLP 28 DAY	% REDUCTION IN TCLP APPARENT	% REDUCTION IN TCLP ACTUAL
VOLATILES						
ACETONE		130	68	1.57	99	98
CHLOROBENZENE		6.7	2.2	4.08	39	-4
1,2-DICHLOROETHANE		13	0.77	0.4	97	95
ETHYLBENZENE		47	28.8	149	-217	-439
STYRENE		11	8	37.5	-241	-480
TETRACHLOROETHYLENE		4.5	1.6	3.38	25	-28
XYLENE		100	37.2	244	-144	-315
SEMIVOLATILES						
ANTHRACENE		3.4	0.04	1.06	69	47
BIS(2-ETHYLHEXYL)PHTHALATE		3	0.01	1.06	65	40
PENTACHLOROPHENOL		3.8	5.9	12.1	-218	-441
INORGANICS (METALS)						
ARSENIC	0.15	9.58	ND	ND	100	100
CADMIUM	0.01	35.3	ND	ND	100	100
CHROMIUM	0.01	0.06	0.06	0.06	0	-70
COPPER	0.02	159.9	0.14	0.17	100	100
LEAD	0.15	70.4	0.39	0.37	99	99
NICKEL	0.04	26.8	0.04	0.04	100	100
ZINC	0.01	395.9	0.32	0.74	100	100

ND - BELOW DETECTION LIMIT

TABLE B-5

TCLP RESULTS FOR SARMs

SARM I
BINDER - KILN DUST
CONCENTRATIONS IN mg/L

	14 DAY	28 DAY
SAMPLE #	14	15
SOIL/BINDER RATIO	1:2	1:3
DILUTION FACTOR	3	4
DENSITY g/cm^3	1.75	1.88
UCS @ 7,14,21,28 DAY	5, 52, 54, 241	176, 211, 215, 81

CONTAMINANT	DET. LIM.	TCLP ACTUAL	TCLP @ 14 DAY	TCLP 28 DAY	% REDUCTION IN TCLP APPARENT	% REDUCTION IN TCLP ACTUAL
VOLATILES						
ACETONE		110	3.87	6.14	94	78
CHLOROBENZENE		5.2	0.11	0.06	99	95
1,2-DICHLOROETHANE		76	0.01	0.1	100	99
ETHYLBENZENE		27	1.54	0.06	100	99
STYRENE		9	0.59	1.06	88	53
TETRACHLOROETHYLENE		3.3	0.12	0.02	99	98
XYLENE		62	2.71	2.04	97	87
SEMIVOLATILE						
ANTHRACENE		2.6	0.05	0.05	98	92
BIS(2-ETHYLHEXYL)PHTHALATE		2.3	0.01	0.05	98	91
PENTACHLOROPHENOL		7.8	0.06	0.13	98	93
INORGANIC (METALS)						
ARSENIC	0.15	ND	ND	ND	—	—
CADMIUM	0.01	0.53	ND	ND	100	100
CHROMIUM	0.01	ND	0.06	0.09	—	—
COPPER	0.02	0.61	0.04	0.03	95	80
LEAD	0.15	0.49	ND	ND	100	100
NICKEL	0.04	0.27	ND	ND	100	100
ZINC	0.01	9.24	0.27	0.62	93	73

ND - BELOW DETECTION LIMIT

TABLE B-6

TCLP RESULTS FOR SARMs

SARM II
BINDER - KILN DUST
CONCENTRATION IN mg/L EXTR

	14 DAY	28 DAY
SAMPLE #	16	16
SOIL/BINDER RATIO	1:1	1:1
DILUTION FACTOR	2	2
DENSITY g/cm3	1.77	1.77
UCS @ 7,14,21,28 DAY		37,60,78,85

CONTAMINANT	TCLP ACTUAL	TCLP @ 14 DAY	TCLP 28 DAY	% REDUCTION IN TCLP APPARENT	% REDUCTION IN TCLP ACTUAL
VOLATILES					
ACETONE	0.92	2.13	1.65	-79	-259
CHLOROBENZENE	0.05	0.01	0.1	-100	-300
1,2-DICHLOROETHANE	0.05	0.01	0.01	80	60
ETHYLBENZENE	0.12	0.28	0.03	75	50
STYRENE	0.03	0.05	0.1	-233	-567
TETRACHLOROETHYLENE	0.05	0.02	0.1	-100	-300
XYLENE	0.3	0.36	0.09	70	40
SEMIVOLATILE					
ANTHRACENE	0.01	0.01	0.01	0	-100
BIS(2-ETHYLHEXYL)PHTHALATE	0.22	0.01	0.05	77	55
PENTACHLOROPHENOL	0.9	0.18	0.04	96	91
INORGANICS (METALS)					
	DET. LIM.				
ARSENIC	0.15	ND	ND	ND	--	--
CADMIUM	0.01	0.73	ND	ND	100	100
CHROMIUM	0.01	ND	0.08	0.05	--	--
COPPER	0.02	0.89	0.07	0.09	90	80
LEAD	0.15	0.7	0.39	0.37	47	-6
NICKEL	0.04	0.4	0.04	0.04	90	80
ZINC	0.01	14.6	0.25	0.78	95	89

ND - BELOW DETECTION LIMIT

TABLE B-7

TCLP RESULTS FOR SARMs

		14 DAY	28 DAY
SARM III	SAMPLE #	21	21
BINDER - KILN DUST	SOIL/BINDER RATIO	1:3	1:3
CONCENTRATION IN mg/L EXTR	DILUTION RATIO	4	4
	DENSITY g/cm^3	1.86	1.86
	UCS @ 7,14,21,28 DAY	46,45,44,80	

CONTAMINANT	DET.LIM.	TCLP ACTUAL	TCLP @ 14 DAY	TCLP 28 DAY	% REDUCTION IN TCLP APPARENT	% REDUCTION IN TCLP ACTUAL
VOLATILES						
ACETONE		7.1	2.17	1.01	86	43
CHLOROBENZENE		0.38	1	0.01	97	89
1,2-DICHLOROETHANE		0.5	0.02	0.1	80	20
ETHYLBENZENE		4.6	0.02	0.08	98	93
STYRENE		0.5	0.01	0.01	98	92
TETRACHLOROETHYLENE		0.33	1	0.01	97	88
XYLENE		11	0.03	0.12	99	96
SEMIVOLATILES						
ANTHRACENE		0.01	0.02	0.11	-1000	-4300
BIS(2-ETHYLHEXYL)PHTHALATE		0.09	0.01	0.11	-22	-389
PENTACHLOROPHENOL		0.34	0.36	0.08	76	6
INORGANICS (METALS)						
ARSENIC	0.15	6.39	0.15	0.21	97	87
CADMIUM	0.01	33.1	ND	ND	100	100
CHROMIUM	0.01	ND	0.22	0.12	--	--
COPPER	0.02	80.7	1.02	0.85	99	96
LEAD	0.15	19.9	13.3	18.3	8	-268
NICKEL	0.04	17.5	ND	ND	100	100
ZINC	0.01	358.5	4.38	4.07	99	95

ND - BELOW DETECTION LIMIT

TABLE B-8

TCLP RESULTS FOR SARMs

SARM IV
BINDER - KILN DUST
CONCENTRATIONS IN mg/L EXT

	14 DAY	28 DAY
SAMPLE #	23	23
SOIL/BINDER RATIO	1:2	1:2
DILUTION FACTOR	3	3
DENSITY g/cm^3	1.83	1.83
UCS @ 7,14,21,28 DAY	39,56,52,52	

CONTAMINANT	TCLP ACTUAL	TCLP @ 14 DAY	TCLP 28 DAY	% REDUCTION IN TCLP APPARENT	% REDUCTION IN TCLP ACTUAL
VOLATILES					
ACETONE	130	24.4	35.2	73	19
CHLOROBENZENE	6.7	0.05	1.26	81	44
1,2-DICHLOROETHANE	13	0.1	0.02	100	100
ETHYLBENZENE	47	7.92	13.5	71	14
STYRENE	11	1.15	4.1	63	-12
TETRACHLOROETHYLENE	4.5	0.11	0.96	79	36
XYLENE	100	10.9	24.1	76	28
SEMIVOLATILES					
ANTHRACENE	3.4	0.01	0.03	99	97
BIS(2-ETHYLHEXYL)PHTHALATE	3	0.01	0.27	91	73
PENTACHLOROPHENOL	3.8	3.2	5.23	-38	-313
INORGANICS (METALS)					
	DET. LIM.				
ARSENIC	0.15	9.58	0.16	0.27	97	92
CADMIUM	0.01	35.3	ND	ND	100	100
CHROMIUM	0.01	0.06	0.11	0.12	-100	-500
COPPER	0.02	159.9	1.88	1.67	99	97
LEAD	0.15	70.4	12.4	21.4	70	9
NICKEL	0.04	26.8	ND	ND	100	100
ZINC	0.01	395.9	4.57	3.77	99	97

ND - BELOW DETECTION LIMIT

TABLE B-9

TCLP RESULTS FOR SARMs

SARM I
BINDER - LIME/FLYASH
CONCENTRATIONS IN mg/L EXTRACT

	14 DAY	28 DAY
SAMPLE #	27	27
SOIL/BINDER RATIO	1:3	1:3
DILUTION FACTOR	4	4
DENSITY g/cm^3	1.54	1.54
UCS @ 7,14,21,28 DAY		20,30,33,47

CONTAMINANT	TCLP ACTUAL	TCLP @ 14 DAY	TCLP 28 DAY	% REDUCTION IN TCLP APPARENT	% REDUCTION IN TCLP ACTUAL
VOLATILES					
ACETONE	110	35.6	43	61	-56
CHLOROBENZENE	5.2	1.3	1.6	69	-23
1,2-DICHLOROETHANE	76	0.4	0.1	100	99
ETHYLBENZENE	27	16.9	18	33	-167
STYRENE	9	0.4	4.1	[illegible]	-82
TETRACHLOROETHYLENE	3.3	1.4	1.5	55	-82
XYLENE	62	21.5	22	65	-42
SEMIVOLATILES					
ANTHRACENE	2.6	0.02	0.02	99	97
BIS(2-ETHYLHEXYL)PHTHALATE	2.3	0.05	0.16	93	72
PENTACHLOROPHENOL	7.8	0.36	0.4	95	79
INORGANICS (METALS)					
	DET. LIM.				
ARSENIC	0.15	ND	ND	ND	--	--
CADMIUM	0.01	0.53	ND	ND	100	100
CHROMIUM	0.01	ND	0.02	0.02	--	--
COPPER	0.02	0.61	0.03	0.03	95	80
LEAD	0.15	0.49	ND	ND	100	100
NICKEL	0.04	0.27	0.04	0.04	85	41
ZINC	0.01	9.2	0.14	ND	100	100

ND - BELOW DETECTION LIMIT

TABLE B-10

TCLP RESULTS FOR SARMs

SARM II
BINDER - LIME/FLYASH
CONCENTRATION IN mg/L EXTR

	14 DAY	28 DAY
SAMPLE #	30	29
SOIL/BINDER RATIO	1:3	1:2
DILUTION FACTOR	4	3
DENSITY g/cm³	1.58	1.56
UCS @ 7,14,21,28 DAY	19, 31, 41, 73	17, 24, 27, 62

CONTAMINANT	TCLP ACTUAL	TCLP @ 14 DAY	TCLP 28 DAY	% REDUCTION IN TCLP APPARENT	% REDUCTION IN TCLP ACTUAL
VOLATILES					
ACETONE	0.92	1.84	3	-226	-878
CHLOROBENZENE	0.05	0.01	0.01	80	40
1,2-DICHLOROETHANE	0.05	0.1	0.01	80	40
ETHYLBENZENE	0.12	0.08	0.15	-25	-275
STYRENE	0.03	0.01	0.03	0	-200
TETRACHLOROETHYLENE	0.05	0.1	0.01	80	40
XYLENE	0.3	0.06	0.2	33	-100
SEMIVOLATILES					
ANTHRACENE	0.01	0.01	0.01	0	-200
BIS(2-ETHYLHEXYL)PHTHALATE	0.22	0.01	0.01	95	86
PENTACHLOROPHENOL	0.9	0.01	0.11	88	63
INORGANICS (METALS)					
	DET. LIM.				
ARSENIC	0.15	ND	ND	ND	--
CADMIUM	0.01	0.73	ND	ND	100
CHROMIUM	0.01	ND	ND	ND	--
COPPER	0.02	0.89	0.02	0.03	97
LEAD	0.15	0.7	ND	ND	100
NICKEL	0.04	0.4	ND	ND	100
ZINC	0.01	14.6	0.22	0.02	100

ND - BELOW DETECTION LIMIT

TABLE B-11

TCLP RESULTS FOR SARMs

		14 DAY	28 DAY
SARM III	SAMPLE #	33	33
BINDER - LIME/FLYASH	SOIL/BINDER RATIO	1:3	1:3
CONCENTRATION IN mg/L EXTRACT	DILUTION RATIO	4	4
	DENSITY g/cm^3	1.49	1.49
	UCS @ 7,14,21,28 DAY	35,49,48,51	

CONTAMINANT	DET. LIM.	TCLP ACTUAL	TCLP @ 14 DAY	TCLP 28 DAY	% REDUCTION IN TCLP APPARENT	% REDUCTION IN TCLP ACTUAL
VOLATILES						
ACETONE		7.1	3.07	2.3	68	-30
CHLOROBENZENE		0.38	0.03	0.02	95	79
1,2-DICHLOROETHANE		0.5	0.01	0.01	98	92
ETHYLBENZENE		4.6	0.55	0.26	94	77
STYRENE		0.5	0.06	0.06	88	52
TETRACHLOROETHYLENE		0.33	0.01	0.02	94	76
XYLENE		11	0.86	0.4	96	85
SEMIVOLATILES						
ANTHRACENE		0.01	0.01	0.01	0	-300
BIS(2-ETHYLHEXYL)PHTHALATE		0.09	0.01	0.02	78	11
PENTACHLOROPHENOL		0.34	0.24	0.3	12	-253
INORGANICS (METALS)						
ARSENIC	0.15	6.39	0.81	0.79	88	51
CADMIUM	0.01	33.1	0.02	0.02	100	100
CHROMIUM	0.01	ND	0.03	0.07	--	--
COPPER	0.02	80.7	2.96	2.59	97	87
LEAD	0.15	19.9	51	51.2	-157	-929
NICKEL	0.04	17.5	ND	0.05	100	99
ZINC	0.01	358.5	3.81	3.97	99	96

ND - BELOW DETECTION LIMIT

TABLE B-12

TCLP RESULTS FOR SARMs

		14 DAY	28 DAY
SARM IV	SAMPLE #	35	36
BINDER - LIME/FLYASH	SOIL/BINDER RATIO	1:2	1:3
CONCENTRATIONS IN mg/L EXT	DILUTION FACTOR	3	4
	DENSITY g/cm^3	1.44	1.52
	UCS @ 7,14,21,28 DAY	30, 39, 36, 41	37, 36, 38, 42

CONTAMINANT	DET.LIM.	TCLP ACTUAL	TCLP @ 14 DAY	TCLP 28 DAY	% REDUCTION IN TCLP APPARENT	% REDUCTION IN TCLP ACTUAL
VOLATILES						
ACETONE		130	42.8	24.1	81	26
CHLOROBENZENE		6.7	0.39	1.7	75	-1
1,2-DICHLOROETHANE		13	0.5	0.65	95	80
ETHYLBENZENE		47	18.1	11.6	75	1
STYRENE		11	2.08	3.59	67	-31
TETRACHLOROETHYLENE		4.5	0.61	2.49	45	-121
XYLENE		100	29.8	22.9	77	8
SEMIVOLATILES						
ANTHRACENE		3.4	0.02	0.01	100	99
BIS(2-ETHYLHEXYL)PHTHALATE		3	0.05	0.1	97	87
PENTACHLOROPHENOL		3.8	14.4	0.25	93	74
INORGANICS (METALS)						
ARSENIC	0.15	9.58	1.61	0.98	90	59
CADMIUM	0.01	35.3	ND	0.02	100	100
CHROMIUM	0.01	0.06	0.07	0.07	--	--
COPPER	0.02	159.9	1.92	2.18	99	95
LEAD	0.15	70.4	91.8	65	8	-269
NICKEL	0.04	26.8	ND	0.05	100	99
ZINC	0.01	395.9	3.22	3.64	99	96

ND - BELOW DETECTION LIMIT

APPENDIX C

DETAILED RESULTS OF UNCONFINED COMPRESSIVE STRENGTH (UCS) TESTS

TABLE C-1

RESULTS OF UCS TESTS
OF SOLIDIFED SARM SAMPLES

SAMPLE #	UNCONFINED COMPRESSIBILITY TEST RESULTS (psi) 7-DAY	14-DAY	21-DAY	28-DAY
1-A	NA	1084	NA	1109
B	NA	587	NA	934
C	NA	1261	NA	1237
mean	NA	977	NA	1093
2-A	NA	1291	NA	1238
B	NA	1329	NA	1247
C	NA	1280	NA	1247
mean	NA	1300	NA	1244
3-A	NA	1276	NA	1288
B	NA	1258	NA	1273
C	NA	717	NA	1350
mean	NA	1084	NA	1304
4-A	NA	1323	NA	1308
B	NA	1294	NA	1167
C	NA	1046	NA	1314
mean	NA	1221	NA	1263
5-A	NA	1316	NA	1298
B	NA	1283	NA	1322
C	NA	1289	NA	1333
mean	NA	1296	NA	1318
6-A	NA	1289	NA	1305
B	NA	1268	NA	1357
C	NA	1289	NA	1147
mean	NA	1282	NA	1270
7-A	NA	30	NA	40
B	NA	34	NA	52
C	NA	33	NA	54
mean	NA	32	NA	49
8-A	NA	137	NA	117
B	NA	114	NA	179
C	NA	124	NA	157
mean	NA	125	NA	151

TABLE C-1 (continued)

RESULTS OF UCS TESTS
OF SOLIDIFED SARM SAMPLES

SAMPLE #	UNCONFINED COMPRESSIBILITY TEST RESULTS (psi) 7-DAY	14-DAY	21-DAY	28-DAY
9-A	NA	84	NA	1165
B	NA	98	NA	1173
C	NA	32	NA	1171
mean	NA	71	NA	1170
10-A	NA	18	NA	18
B	NA	NA	NA	17
C	NA	14	NA	14
mean	NA	16	NA	16
11-A	NA	172	NA	199
B	NA	168	NA	144
C	NA	163	NA	135
mean	NA	167	NA	159
12-A	NA	190	NA	262
B	NA	157	NA	303
C	NA	184	NA	388
mean	NA	177	NA	318
13-A	<5	75	71	107
B	<5	77	100	115
C	<5	67	107	116
mean	<5	73	93	113
14-A	<5	52	48	230
B	<5	51	52	249
C	<5	52	63	245
mean	<5	52	54	241
15-A	178	203	215	75
B	160	204	216	76
C	189	225	NA	92
mean	176	211	215	81
16-A	36	64	68	85
B	38	53	90	86
C	39	63	78	85
mean	38	60	78	85

TABLE C-1 (con*inued)

RESULTS OF UCS TESTS
OF SOLIDIFED SARM SAMPLES

SAMPLE #	UNCONFINED COMPRESSIBILITY TEST RESULTS (psi) 7-DAY	14-DAY	21-DAY	28-DAY
17-A	127	171	208	222
B	131	148	174	205
C	127	252	109	220
mean	128	190	164	216
18-A	191	226	334	246
B	174	225	258	245
C	183	224	232	265
mean	183	225	275	252
19-A	29	36	35	39
B	39	40	37	40
C	30	35	39	36
mean	33	37	37	39
20-A	33	34	40	37
B	34	43	44	36
C	33	38	39	44
mean	33	38	41	39
21-A	36	41	44	72
B	69	39	37	107
C	32	54	50	61
mean	46	45	44	80
22-A	25	29	29	31
B	30	25	29	36
C	30	31	23	30
mean	28	28	27	32
23-A	38	52	56	53
B	42	59	45	48
C	37	56	56	56
mean	39	56	52	52
24-A	37	37	37	43
B	37	37	22	40
C	33	41	40	38
mean	36	38	33	40

TABLE C-1 (continued)

RESULTS OF UCS TESTS
OF SOLIDIFED SARM SAMPLES

SAMPLE #	UNCONFINED COMPRESSIBILITY TEST RESULTS (psi) 7-DAY	14-DAY	21-DAY	28-DAY
25-A	22	28	31	34
B	25	28	25	27
C	26	26	23	36
mean	24	27	26	32
26-A	23	28	35	45
B	22	30	35	39
C	22	29	32	38
mean	22	29	34	40
27-A	20	32	35	49
B	19	29	31	47
C	19	30	32	44
mean	20	30	33	47
28-A	8	17	18	28
B	11	17	16	31
C	11	17	18	28
mean	10	17	17	29
29-A	16	16	32	61
B	17	29	24	64
C	18	28	25	67
mean	17	24	27	63
30-A	22	38	45	73
B	19	26	41	75
C	17	31	37	72
mean	19	31	41	73
31-A	24	31	28	30
B	20	28	33	32
C	21	28	26	30
mean	22	29	29	31
32-A	27	33	38	39
B	32	34	34	35
C	32	32	37	36
mean	30	33	36	37

TABLE C-1 (continued)

RESULTS OF UCS TESTS
OF SOLIDIFED SARM SAMPLES

SAMPLE #	UNCONFINED COMPRESSIBILITY TEST RESULTS (psi) 7-DAY	14-DAY	21-DAY	28-DAY
33-A	34	47	52	49
B	32	53	51	52
C	38	47	42	52
mean	35	49	48	51
34-A	38	30	31	35
B	32	34	36	39
C	35	34	38	40
mean	35	33	35	38
35-A	29	NA	40	44
B	30	37	37	40
C	31	40	33	38
mean	30	39	36	41
36-A	34	40	35	39
B	39	35	36	42
C	38	33	42	45
mean	37	36	38	42

NOTE: Binder for Sample Nos. 1-12 = Portland cement
Binder for Sample Nos. 13-24 = Kiln dust
Binder for Sample Nos. 25-36 = Lime/flyash

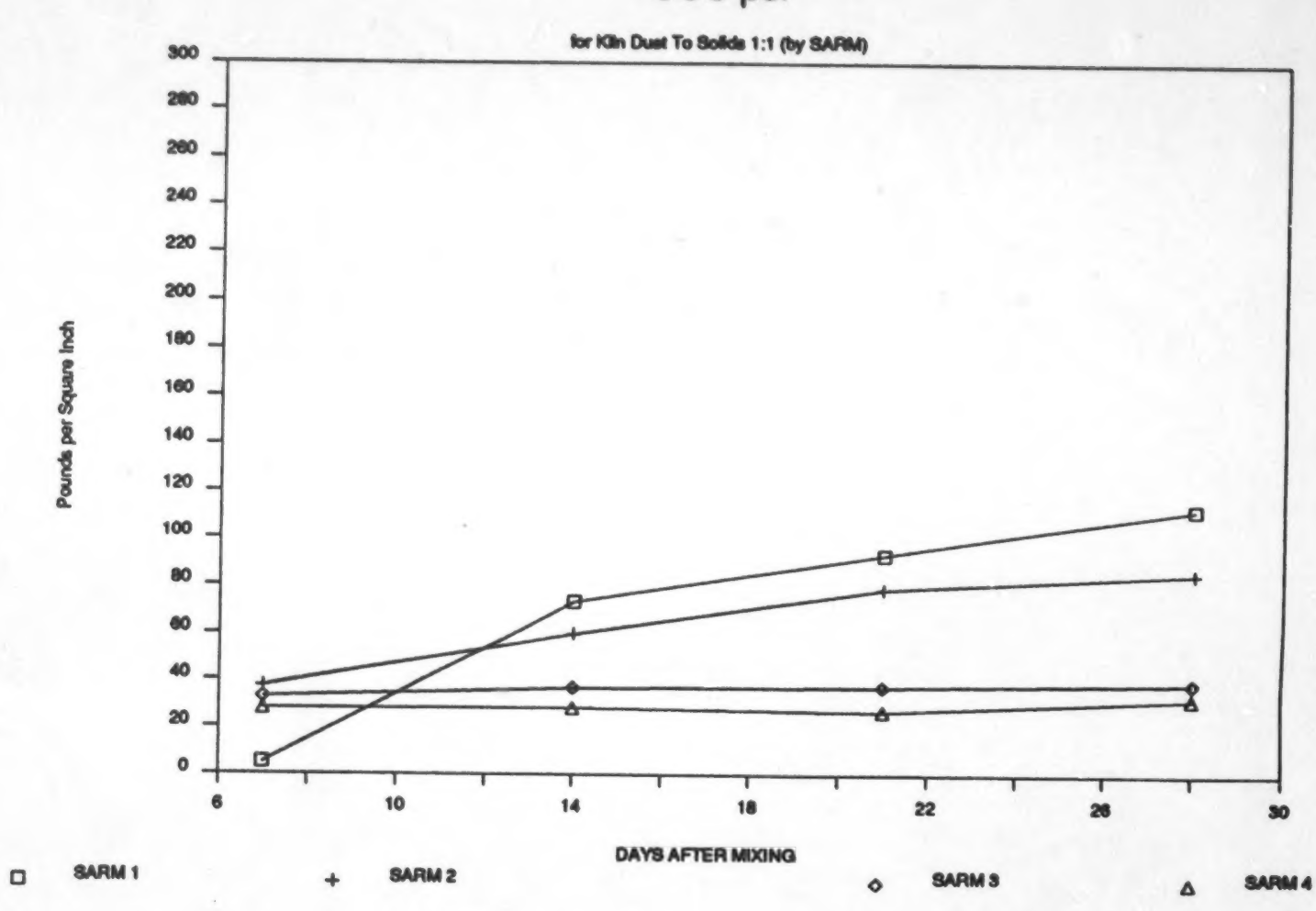

Figure C-1. Change in UCS due to curing time

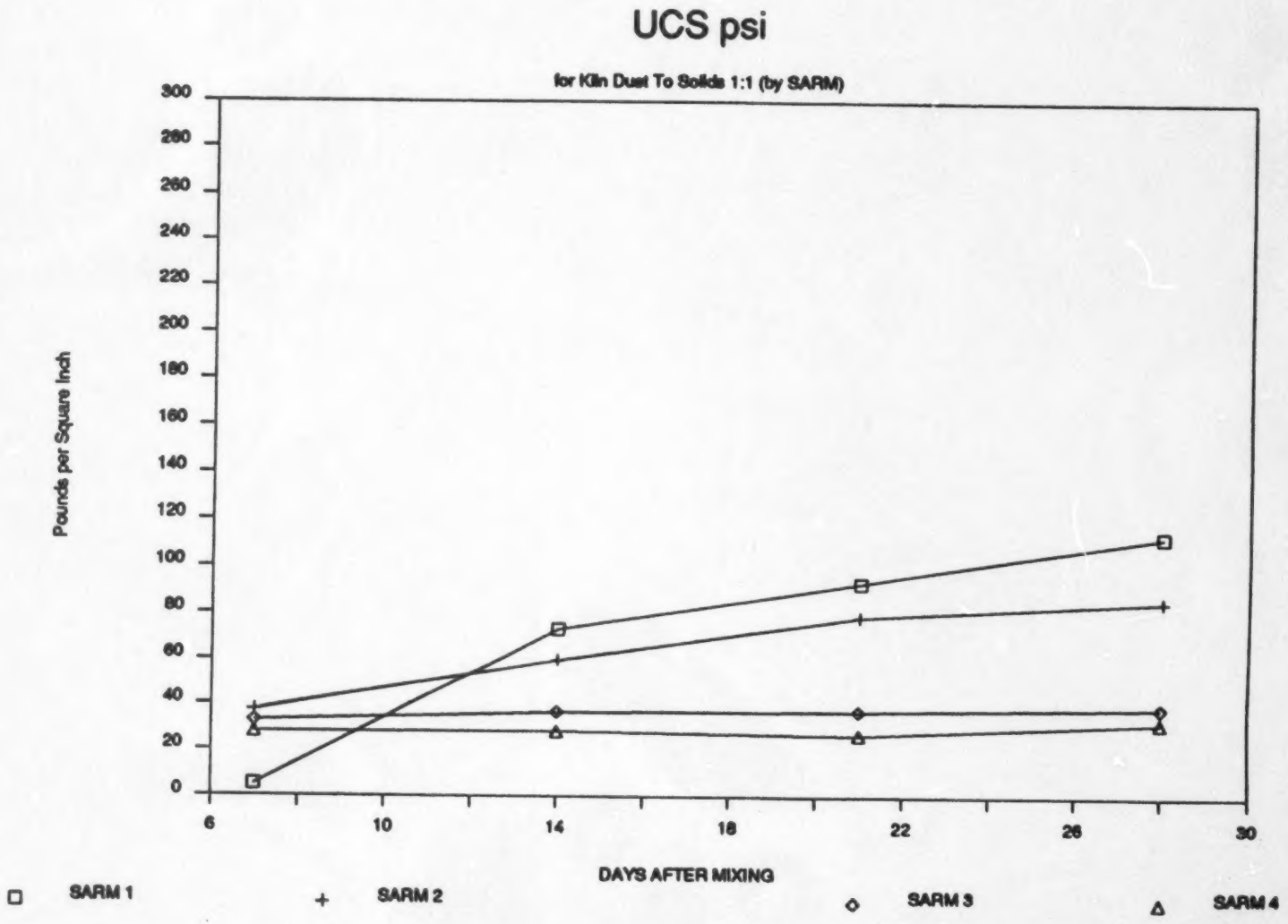

Figure C-1. Change in UCS due to curing time

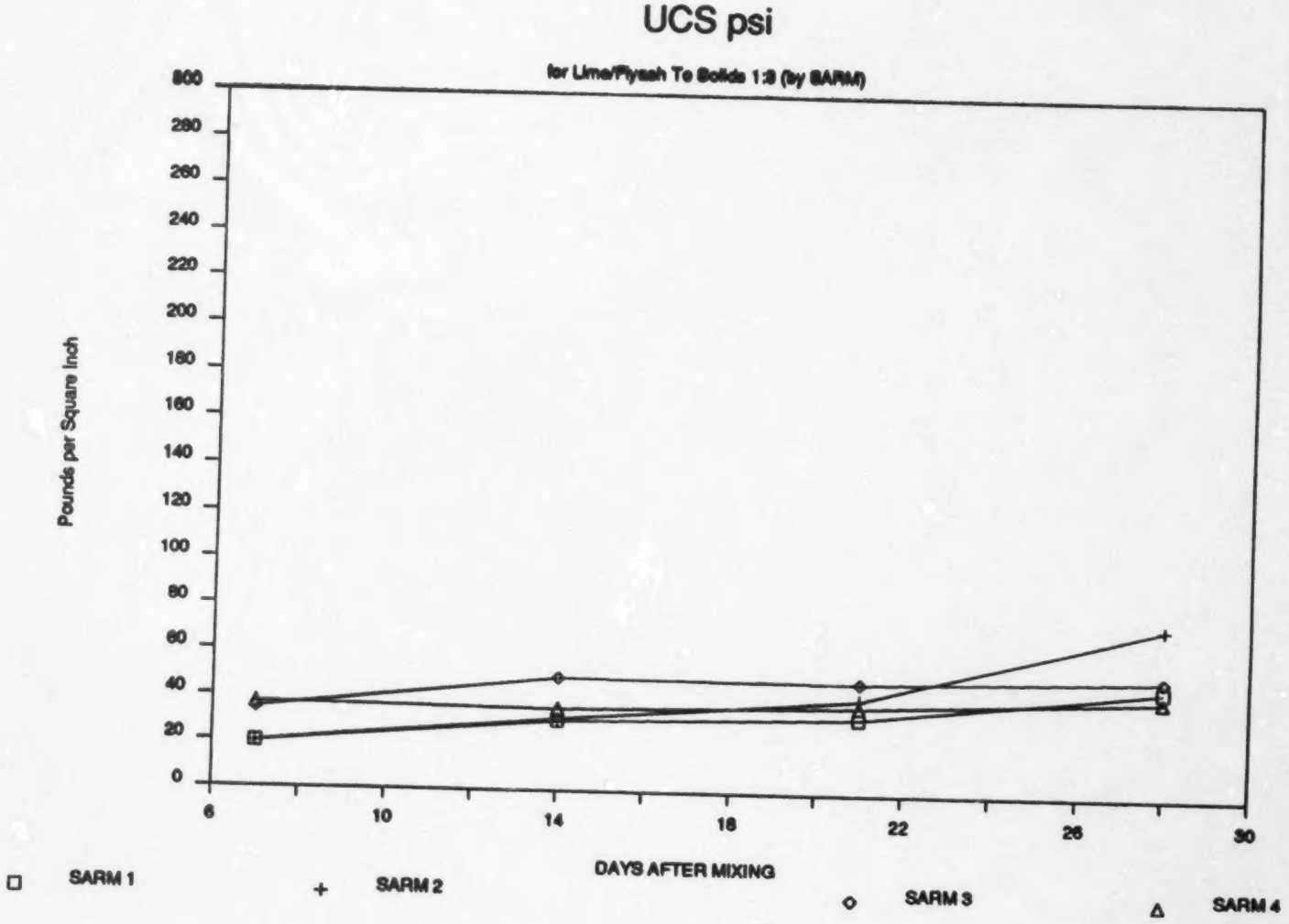

Figure C-6. Change in UCS due to curing time

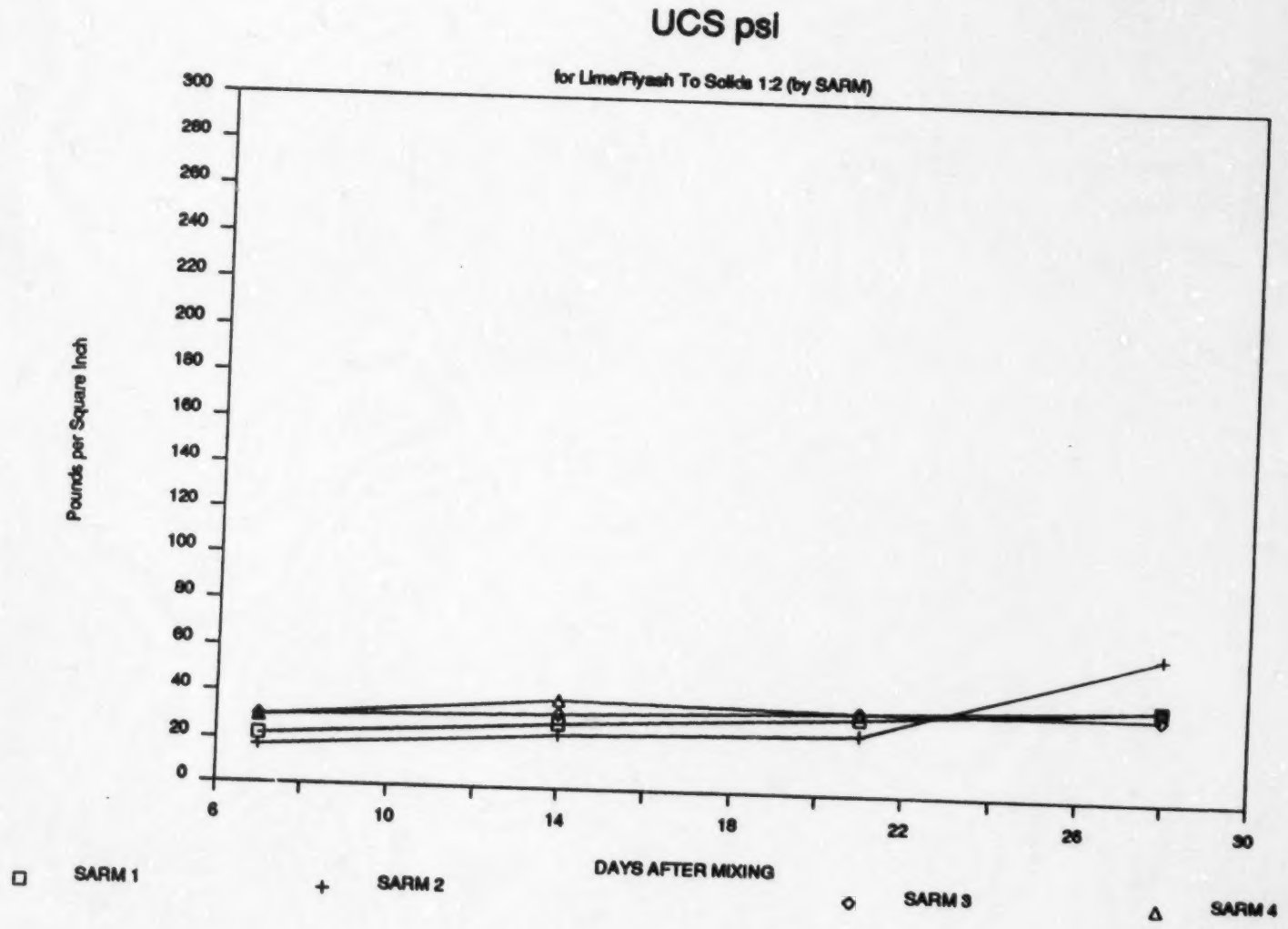

Figure C-5. Change in UCS due to curing time

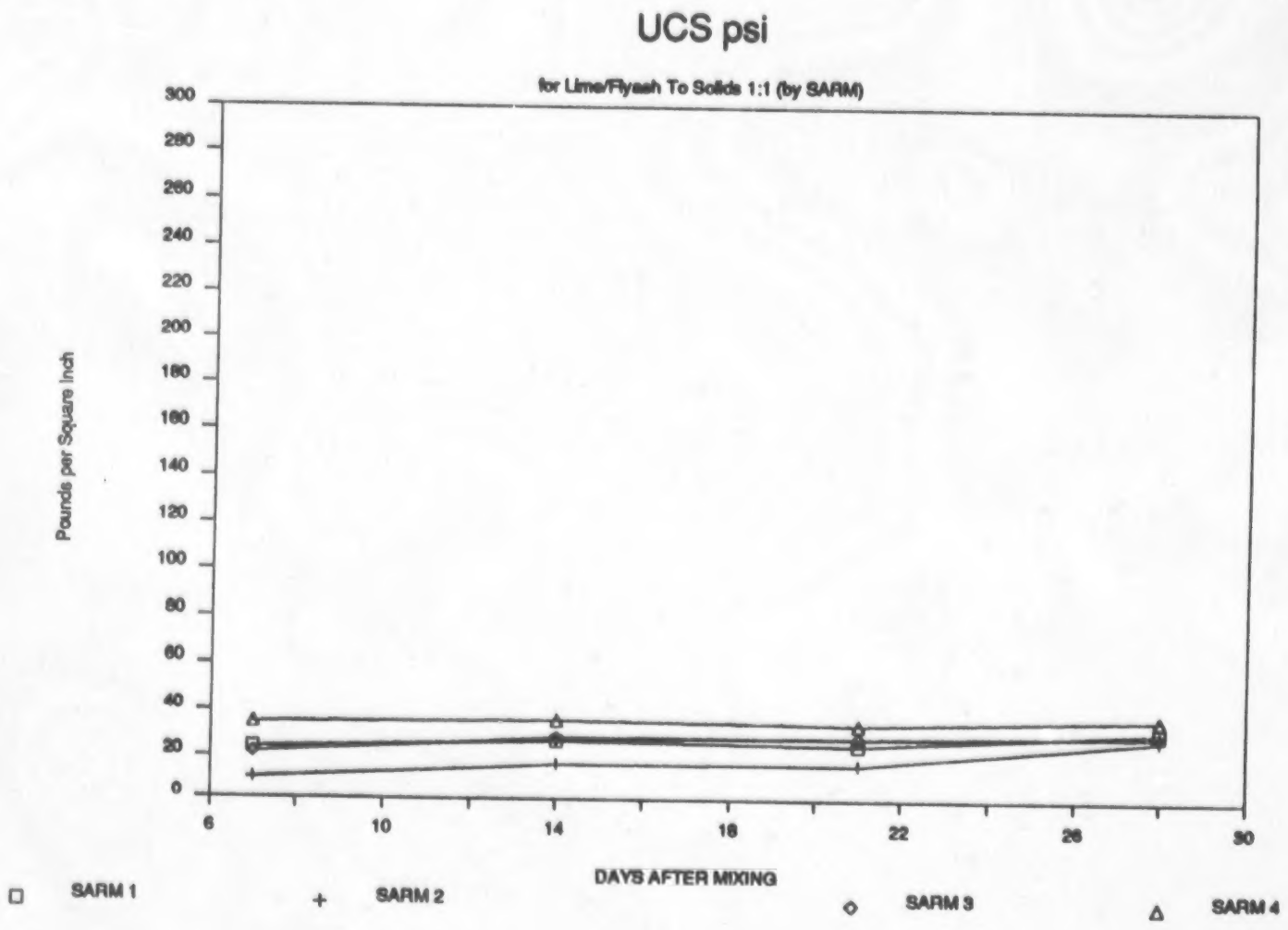

Figure C-4. Change in UCS due to curing time

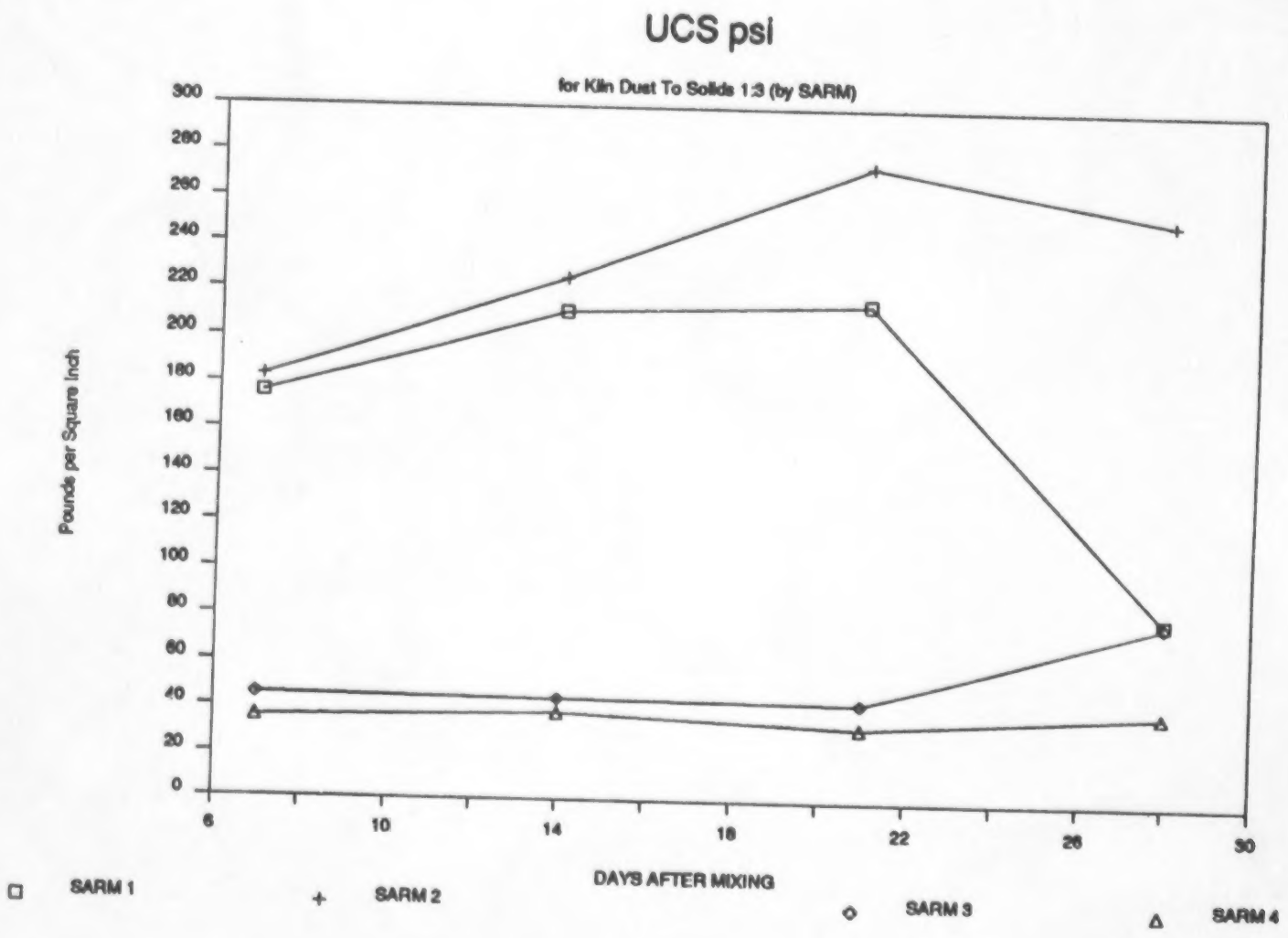

Figure C-3. Change in UCS due to curing time

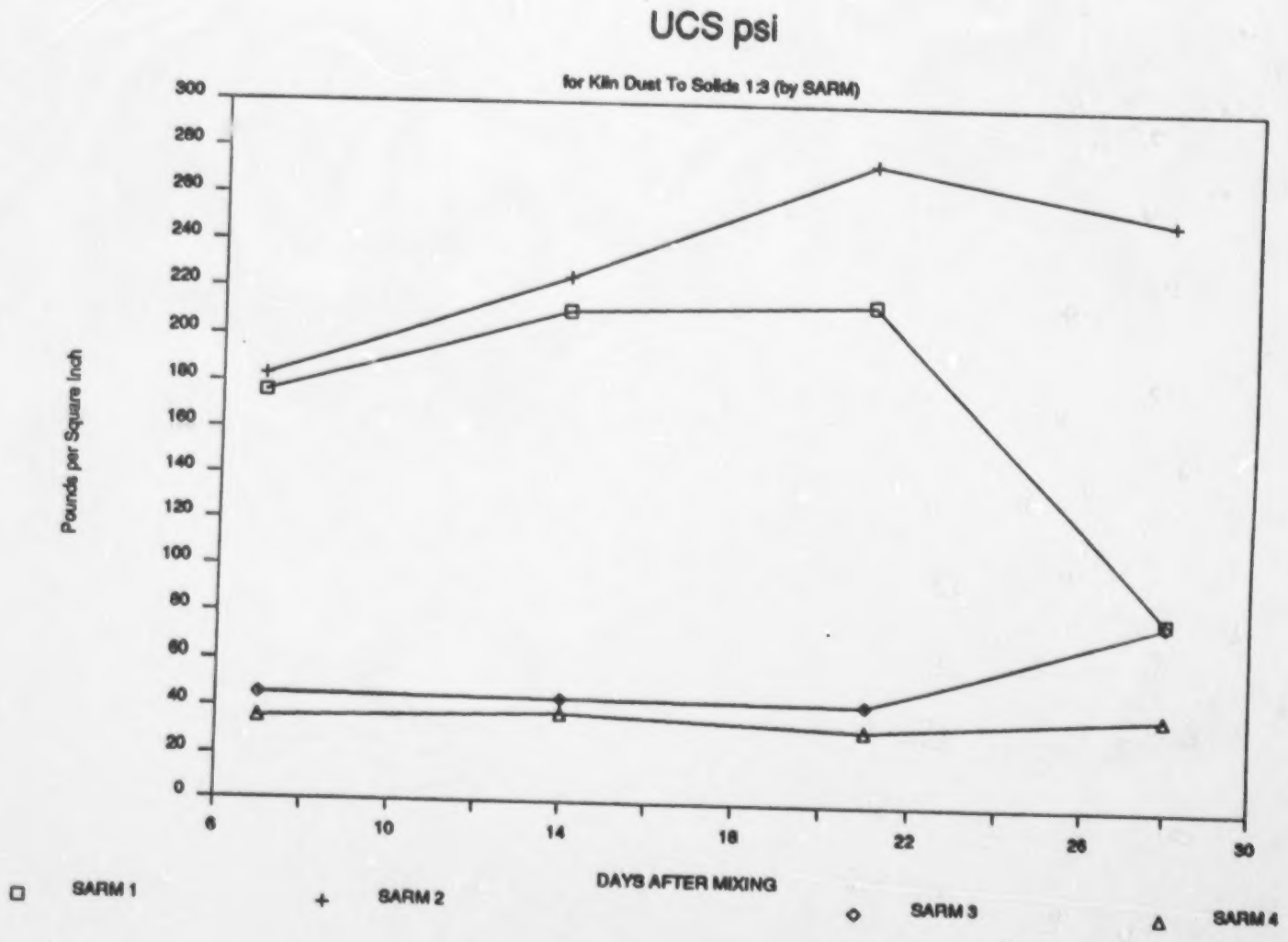

Figure C-3. Change in UCS due to curing time

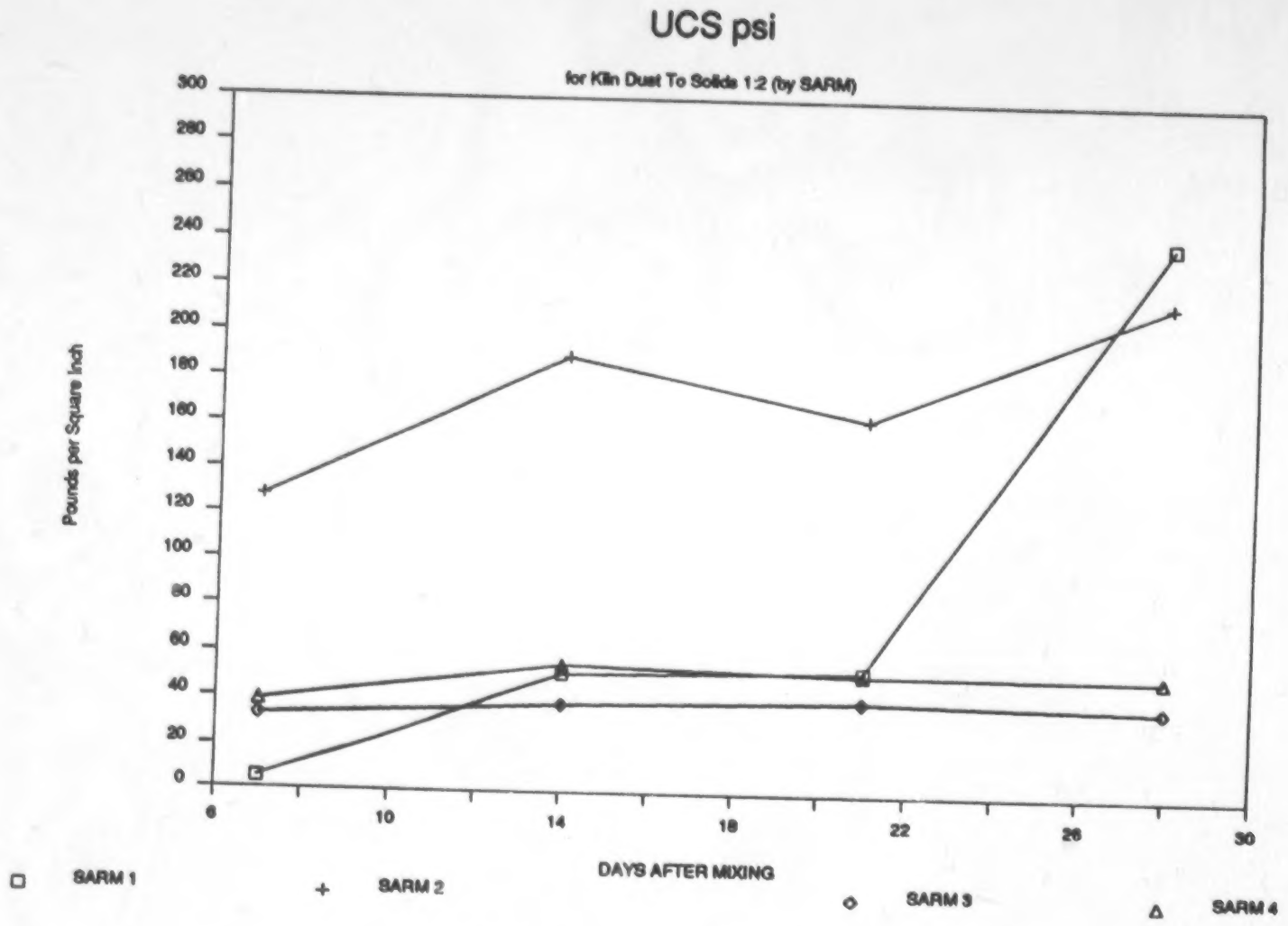

Figure C-2. Change in UCS due to curing time